CHAPTER 2
ASSEMBLY AND RIGGING

GENERAL

This chapter includes both assembly and rigging since the subjects are directly related. Assembly involves putting together the component sections of the aircraft, such as wing sections, empennage units, nacelles, and landing gear. Rigging is the final adjustment and alignment of the various component sections to provide the proper aerodynamic reaction.

Two important considerations in all assembly and rigging operations are: (1) Proper operation of the component in regard to its aerodynamic and mechanical function, and (2) maintaining the aircraft's structural integrity by the correct use of materials, hardware, and safetying devices. Improper assembly and rigging may result in certain members being subjected to loads greater than those for which they were designed.

Assembly and rigging must be done in accordance with the requirements prescribed by the aircraft manufacturer. These procedures are usually detailed in the applicable maintenance or service manuals. The Aircraft Specification or Type Certificate Data Sheets also provide valuable information regarding control surface travel.

The rigging of control systems varies with each type of aircraft, therefore, it would be impracticable to define a precise procedure. However, certain principles apply in all situations and these will be discussed in this chapter. It is essential that the aircraft manufacturer's instructions be followed when rigging an aircraft.

THEORY OF FLIGHT

Numerous comprehensive texts have been written about the aerodynamics involved in the flight of an aircraft. It is unnecessary that a mechanic be totally versed on the subject. However, he must understand the relationships between the atmosphere, the aircraft, and the forces acting on it in flight, in order to make intelligent decisions affecting the flight safety of both airplanes and helicopters.

Understanding why the aircraft is designed with a particular type of primary and secondary control system, and why the surfaces must be aerodynamically smooth, becomes essential when maintaining today's complex aircraft.

AERODYNAMICS

Theory of flight deals with aerodynamics. The term aerodynamics is derived from the combination of two Greek words—"aer" meaning air, and "dyne" meaning force of power. Thus, when aero is joined with dynamics, we have aerodynamics, meaning the study of objects in motion through the air and the forces that produce or change such motion.

Aerodynamics is the science of the action of air on an object. It is further defined as that branch of dynamics which deals with the motion of air and other gases, with the forces acting upon an object in motion through the air, or with an object which is stationary in a current of air. In effect, aerodynamics is concerned with three distinct parts. These parts may be defined as the aircraft, the relative wind, and the atmosphere.

THE ATMOSPHERE

Before discussing the fundamentals of the theory of flight, there are several basic ideas that must be considered. An aircraft operates in the air; therefore, the properties of air that affect aircraft control and performance must be understood.

Air is a mixture of gases composed principally of nitrogen and oxygen. Since air is a combination of gases, it follows the laws of gases. Air is considered a fluid because it answers the definition of a fluid, namely, a substance which may be made to flow or change its shape by the application of moderate pressure. Air has weight, since something lighter than air, such as a balloon filled with helium, will rise in the air.

PRESSURE

The deeper a diver goes beneath the surface of the ocean, the greater the pressure becomes on his body due to the weight of the water overhead. Since air also has weight, the greater the depth from the outer surface of the atmosphere, the greater the pressure. If a 1-in. square column of air extending from sea level to the "top" of the atmosphere could be weighed, it would be found to weigh about 14.7 lbs. Thus, atmospheric pressure at sea level is 14.7 p.s.i. (pounds per square inch). However, pounds per square inch is rather a crude unit for the measurement of a light substance such as air. Therefore, atmospheric pressure is usually measured in terms of inches of mercury.

The apparatus for measuring atmospheric pressure is shown in figure 2-1. A glass tube, 36 in. long, open at one end, and closed at the other, is filled with mercury. The open end is sealed temporarily and then submerged into a small container partly filled with mercury, after which the end is unsealed. This allows the mercury in the tube to descend, leaving a vacuum at the top of the tube. Some of the mercury flows into the container while a portion of it remains in the tube. The weight of the atmosphere pressing on the mercury in the open container exactly balances the weight of the mercury in the tube, which has no atmospheric pressure pushing down on it due to the vacuum in the top of the tube. As the pressure of the surrounding air decreases or increases, the mercury column lowers or rises correspondingly. At sea level the height of the mercury in the tube measures approximately 29.92 in., although it varies slightly with atmospheric conditions.

An important consideration is that atmospheric pressure varies with altitude. The higher an object rises above sea level, the lower the pressure. Various atmospheric conditions have a definite relation to flying. The effect of temperature, altitude, and density of the air on aircraft performance is discussed in the following paragraphs.

DENSITY

Density is a term that means weight per unit volume. Since air is a mixture of gases, it can be compressed. If the air in one container is under one-half as much pressure as the air in another identical container, the air under the greater pressure weighs twice as much as that in the container under lower pressure. The air under greater pressure is twice as dense as that in the other container. For equal weights of air, that which is under the greater pressure occupies only half the volume of that under half the pressure.

The density of gases is governed by the following rules:

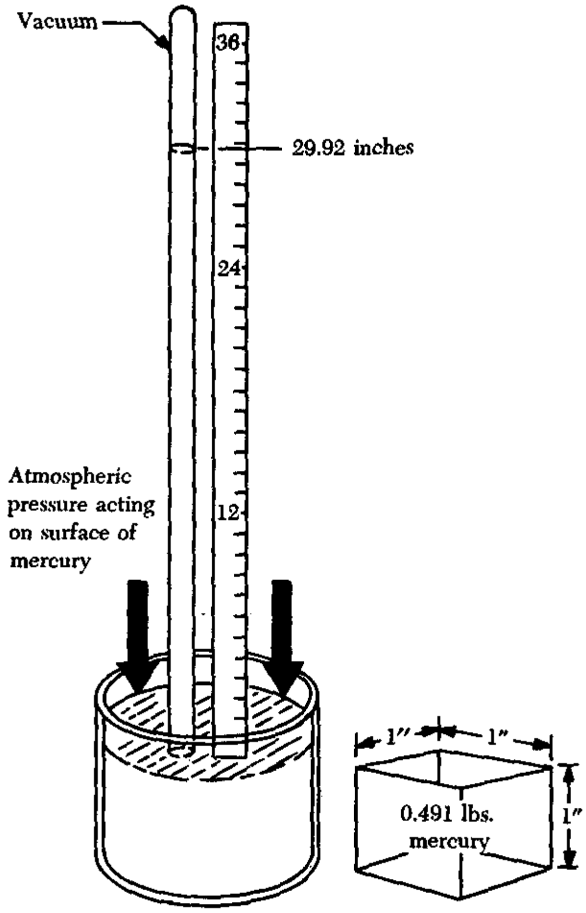


FIGURE 2-1. Measurement of atmospheric pressure.

(1) Density varies in direct proportion with the pressure.

(2) Density varies inversely with the temperature.

Thus, air at high altitudes is less dense than air at low altitudes, and a mass of hot air is less dense than a mass of cool air.

Changes in density affect the aerodynamic performance of aircraft. With the same horsepower, an aircraft can fly faster at a high altitude where the density is low than at a low altitude where the density is great. This is because air offers less resistance to the aircraft when it contains a smaller number of air particles per unit volume.

HUMIDITY

Humidity is the amount of water vapor in the air. The maximum amount of water vapor that air can hold varies with the temperature. The higher the temperature of the air, the more water vapor it can absorb. By itself, water vapor weighs approximately five-eighths as much as an equal amount of perfectly dry air. Therefore, when air contains water vapor it is not as heavy as air containing no moisture.

Assuming that the temperature and pressure remain the same, the density of the air varies inversely with the humidity. On damp days the air density is less than on dry days. For this reason, an aircraft requires a longer runway for takeoff on damp days than it does on dry days.

BERNOULLI'S PRINCIPLE AND SUBSONIC FLOW

Bernoulli's principle states that when a fluid (air) flowing through a tube reaches a constriction, or narrowing of the tube, the speed of the fluid flowing through that constriction is increased and its pressure is decreased. The cambered (curved) surface of an airfoil (wing) affects the airflow exactly as a constriction in a tube affects airflow. This resemblance is illustrated in figure 2–2.

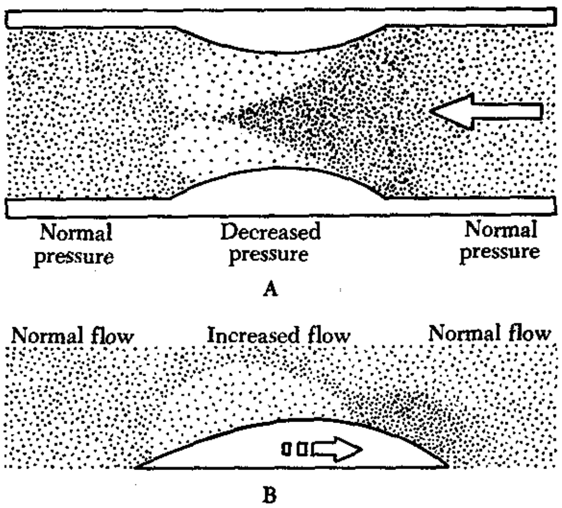


FIGURE 2–2. Bernoulli's principle.

Diagram A of figure 2–2 illustrates the effect of air passing through a constriction in a tube. In B, the air is flowing past a cambered surface, such as an airfoil, and the effect is similar to that of air passing through a restriction.

As the air flows over the upper surface of an airfoil, its speed or velocity increases and its pressure decreases. An area of low pressure is thus formed. There is an area of greater pressure on the lower surface of the airfoil, and this greater pressure tends to move the wing upward. This difference in pressure between the upper and lower surfaces of the wing is called lift. Three-fourths of the total lift of an airfoil is the result of the decrease in pressure over the upper surface. The impact of air on the under surface of an airfoil produces the other one-fourth of the total lift.

An aircraft in flight is acted upon by four forces:

(1) Gravity, or weight, the force that pulls the aircraft toward the earth.
(2) Lift, the force that pushes the aircraft upward.
(3) Thrust, the force that moves the aircraft forward.
(4) Drag, the force that exerts a braking action.

MOTION

Motion is the act or process of changing place or position. An object may be in motion with respect to one object and motionless with respect to another. For example, a person sitting quietly in an aircraft flying at 200 knots is at rest or motionless with respect to the aircraft; however, the person is in motion with respect to the air or the earth, the same as is the aircraft.

Air has no force or power, except pressure, unless it is in motion. When it is moving, however, its force becomes apparent. A moving object in motionless air has a force exerted on it as a result of its own motion. It makes no difference in the effect then, whether an object is moving with respect to the air or the air is moving with respect to the object.

The flow of air around an object caused by the movement of either the air or the object, or both, is called the relative wind.

Velocity and Acceleration

The terms "speed" and "velocity" are often used interchangeably, but they do not mean the same. Speed is the rate of motion, and velocity is the rate of motion in a particular direction in relation to time.

An aircraft starts from New York City and flies 10 hrs. at an average speed of 260 m.p.h. At the end of this time the aircraft may be over the Atlantic Ocean, the Pacific Ocean, the Gulf of Mexico, or, if its flight were in a circular path, it may even be back over New York. If this same aircraft flew at a velocity of 260 m.p.h. in a southwestward direction, it would arrive in Los Angeles in about 10 hrs. Only the rate of motion is indicated in the first example and denotes the speed of the aircraft. In the last example, the particular direction is included with the rate of motion, thus, denoting the velocity of the aircraft.

Acceleration is defined as the rate of change of velocity. An aircraft increasing in velocity is an example of positive acceleration, while another aircraft reducing its velocity is an example of negative acceleration. (Positive acceleration is often referred to as acceleration and negative acceleration as deceleration.)

Newton's Laws of Motion

The fundamental laws governing the action of air about a wing are Newton's laws of motion.

Newton's first law is normally referred to as the law of inertia. It simply means that a body at rest will not move unless force is applied to it. If it is moving at uniform speed in a straight line, force must be applied to increase or decrease that speed.

Since air has mass, it is a "body" in the meaning of the law. When an aircraft is on the ground with its engines stopped, inertia keeps the aircraft at rest. An aircraft is moved from its state of rest by the thrust force created by the propeller, by the expanding exhaust gases, or both. When it is flying at uniform speed in a straight line, inertia tends to keep the aircraft moving. Some external force is required to change the aircraft from its path of flight.

Newton's second law, that of force, also applies to objects. This law states that if a body moving with uniform speed is acted upon by an external force, the change of motion will be proportional to the amount of the force, and motion will take place in the direction in which the force acts. This law may be stated mathematically as follows:

$$\text{Force} = \text{mass} \times \text{acceleration } (F = ma).$$

If an aircraft is flying against a headwind, it is slowed down. If the wind is coming from either side of the aircraft's heading, the aircraft is pushed off course unless the pilot takes corrective action against the wind direction.

Newton's third law is the law of action and reaction. This law states that for every action (force) there is an equal and opposite reaction (force). This law is well illustrated by the action of a swimmer's hands. He pushes the water aft and thereby propels himself forward, since the water resists the action of his hands. When the force of lift on an aircraft's wing equals the force of gravity, the aircraft maintains level flight.

The three laws of motion which have been discussed are closely related and apply to the theory of flight. In many cases, all three laws may be operating on an aircraft at the same time.

AIRFOILS

An airfoil is a surface designed to obtain a desirable reaction from the air through which it moves. Thus, we can say that any part of the aircraft which converts air resistance into a force useful for flight is an airfoil. The blades of a propeller are so designed that when they rotate, their shape and position cause a higher pressure to be built up behind them than in front of them so that they will pull the aircraft forward. The profile of a conventional wing, shown in figure 2-3, is an excellent example of an airfoil. Notice that the top surface of the wing profile has greater curvature than the lower surface.

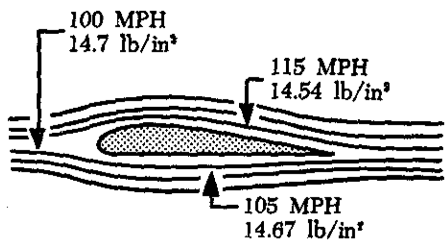


FIGURE 2-3. Airflow over a wing section.

The difference in curvature of the upper and lower surfaces of the wing builds up the lift force. Air flowing over the top surface of the wing must reach the trailing edge of the wing in the same amount of time as the air flowing under the wing. To do this, the air passing over the top surface moves at a greater velocity than the air passing below the wing because of the greater distance it must travel along the top surface. This increased velocity, according to Bernoulli's principle, means a corresponding decrease in pressure on the surface. Thus, a pressure differential is created between the upper and lower surfaces of the wing, forcing the wing upward in the direction of the lower pressure.

The theoretical amount of lift of the airfoil at a velocity of 100 m.p.h. can be determined by sampling the pressure above and below the airfoil at the point of greatest air velocity. As shown in figure 2-3, this pressure is 14.54 p.s.i. above the airfoil. Subtracting this pressure from the pressure below the airfoil, 14.67, gives a difference in pressure of 0.13 p.s.i. Multiplying 0.13 by 144 (number of square inches in a square foot) shows that each square foot of this wing will lift 18.72 pounds. Thus, it can be seen that a small pressure differential across an airfoil section can produce a large lifting force. Within limits, lift can be increased by increasing the angle of attack, the wing area, the freestream velocity, or the density of the air, or by changing the shape of the airfoil.

Angle of Attack

Before beginning the discussion on angle of attack and its effect on airfoils, we shall first consider the terms "chord" and "center of pressure."

The chord of an airfoil or wing section is an imaginary straight line which passes through the section from the leading edge to the trailing edge, as shown in figure 2–4. The chord line provides one side of an angle which ultimately forms the angle of attack. The other side of the angle is formed by a line indicating the direction of the relative airstream. Thus, angle of attack is defined as the angle between the chord line of the wing and the direction of the relative wind. This is not to be confused with the angle of incidence, which is the angle between the chord line of the wing and the longitudinal axis of the aircraft.

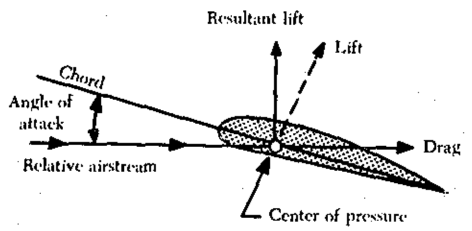


FIGURE 2–4. Positive angle of attack.

On each minute part of an airfoil or wing surface, a small force is present. This force is different in magnitude and direction from any forces acting on other areas forward or rearward from this point. It is possible to add all of these small forces mathematically, and the sum is called the resultant force (lift). This resultant force has magnitude, direction, and location, and can be represented as a vector, as shown in figure 2–4. The point of intersection of the resultant force line with the chord line of the airfoil is called the center of pressure. The center of pressure moves along the airfoil chord as the angle of attack changes. Throughout most of the flight range, the center of pressure moves forward with increasing angle of attack and rearward as the angle of attack decreases. The effect of increasing angle of attack on the center of pressure is shown in figure 2–5.

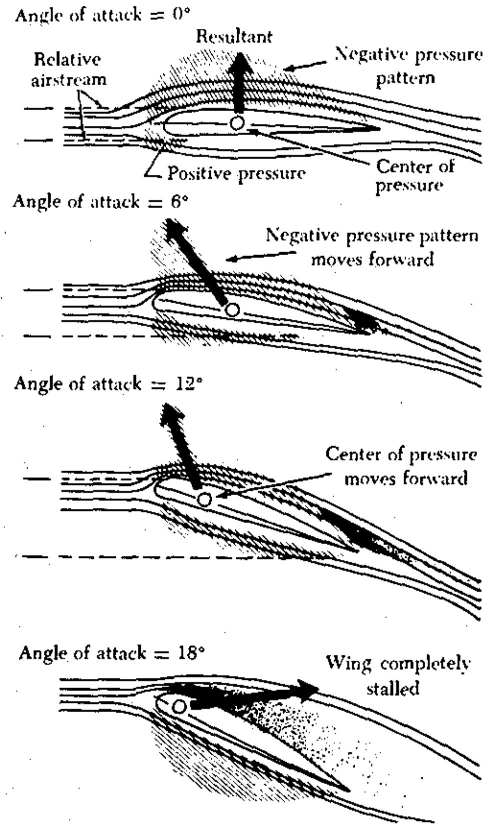


FIGURE 2–5. Effect of increasing angle of attack.

The angle of attack changes as the aircraft's attitude changes. Since the angle of attack has a great deal to do with determining lift, it is given primary consideration when designing airfoils. In a properly designed airfoil, the lift increases as the angle of attack is increased.

When the angle of attack is increased gradually toward a positive angle of attack, the lift component increases rapidly up to a certain point and then suddenly begins to drop off. During this action the drag component increases slowly at first and then rapidly as lift begins to drop off.

When the angle of attack increases to the angle of maximum lift, the burble point is reached. This is known as the critical angle. When the critical angle is reached, the air ceases to flow smoothly over the top surface of the airfoil and begins to burble, or eddy. This means that air breaks away from the upper camber line of the wing. What was formerly the area of decreased pressure is now filled by this burbling air. When this occurs, the amount of lift drops and drag becomes excessive. The force of gravity exerts itself, and the nose of the aircraft drops. Thus we see that the burble point is the stalling angle.

As we have seen, the distribution of the pressure forces over the airfoil varies with the angle of attack. The application of the resultant force, that is, the center of pressure, varies correspondingly. As this angle increases, the center of pressure moves forward; and as the angle decreases, the center of pressure moves back. The unstable travel of the center of pressure is characteristic of practically all airfoils.

Angle of Incidence

The acute angle which the wing chord makes with the longitudinal axis of the aircraft is called the angle of incidence (figure 2–6), or the angle of wing setting. The angle of incidence in most cases is a fixed, built-in angle. When the leading edge of the wing is higher than the trailing edge, the angle of incidence is said to be positive. The angle of incidence is negative when the leading edge is lower than the trailing edge of the wing.

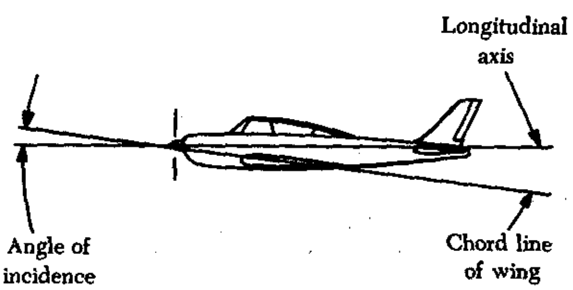


FIGURE 2–6. Angle of incidence.

Wing Area

Wing area is measured in square feet and includes the part blanked out by the fuselage. Wing area is adequately described as the area of the shadow cast by the wing at high noon. Tests show that lift and drag forces acting on a wing are roughly proportional to the wing area. This means that if the wing area is doubled, all other variables remaining the same, the lift and drag created by the wing is doubled. If the area is tripled, lift and drag are tripled.

Shape of the Airfoil

The shape of the airfoil determines the amount of turbulence or skin friction that it will produce. The shape of a wing consequently affects the efficiency of the wing.

Airfoil section properties differ from wing or aircraft properties because of the effect of the wing planform. A wing may have various airfoil sections from root to tip, with taper, twist, and sweepback. The resulting aerodynamic properties of the wing are determined by the action of each section along the span.

Turbulence and skin friction are controlled mainly by the fineness ratio, which is defined as the ratio of the chord of the airfoil to the maximum thickness. If the wing has a high fineness ratio, it is a very thin wing. A thick wing has a low fineness ratio. A wing with a high fineness ratio produces a large amount of skin friction. A wing with a low fineness ratio produces a large amount of turbulence. The best wing is a compromise between these two extremes to hold both turbulence and skin friction to a minimum.

Efficiency of a wing is measured in terms of the lift over drag (L/D) ratio. This ratio varies with the angle of attack but reaches a definite maximum value for a particular angle of attack. At this angle, the wing has reached its maximum efficiency. The shape of the airfoil is the factor which determines the angle of attack at which the wing is most efficient; it also determines the degree of efficiency. Research has shown that the most efficient airfoils for general use have the maximum thickness occurring about one-third of the way back from the leading edge of the wing.

High-lift wings and high-lift devices for wings have been developed by shaping the airfoils to produce the desired effect. The amount of lift produced by an airfoil will increase with an increase in wing camber. Camber refers to the curvature of an airfoil above and below the chord line surface. Upper camber refers to the upper surface, lower camber to the lower surface, and mean camber to the mean line of the section. Camber is positive when departure from the chord line is outward, and negative when it is inward. Thus, high-lift wings have a large positive camber on the upper surface and a slight negative camber on the lower surface. Wing flaps cause an ordinary wing to approximate this same condition by increasing the upper camber and by creating a negative lower camber.

It is also known that the larger the wingspan as compared to the chord, the greater the lift obtained. This comparison is called aspect ratio. The higher the aspect ratio, the greater the lift. In spite of the benefits from an increase in aspect ratio, it was found that definite limitations were of structural and drag considerations.

On the other hand, an airfoil that is perfectly streamlined and offers little wind resistance sometimes does not have enough lifting power to take the aircraft off the ground. Thus, modern aircraft have airfoils which strike a medium between extremes, with the shape varying according to the aircraft for which it is designed.

CENTER OF GRAVITY

Gravity is the pulling force that tends to draw all bodies in the earth's sphere to the center of the earth. The center of gravity may be considered as a point at which all the weight of the aircraft is concentrated. If the aircraft were supported at its exact center of gravity, it would balance in any position. Center of gravity is of major importance in an aircraft, for its position has a great bearing upon stability.

The center of gravity is determined by the general design of the aircraft. The designer estimates how far the center of pressure will travel. He then fixes the center of gravity in front of the center of pressure for the corresponding flight speed in order to provide an adequate restoring moment for flight equilibrium.

THRUST AND DRAG

An aircraft in flight is the center of a continuous battle of forces. Actually, this conflict is not as violent as it sounds, but it is the key to all maneuvers performed in the air. There is nothing mysterious about these forces; they are definite and known. The directions in which they act can be calculated; and the aircraft itself is designed to take advantage of each of them. In all types of flying, flight calculations are based on the magnitude and direction of four forces: weight, lift, drag, and thrust. (See fig. 2–7.)

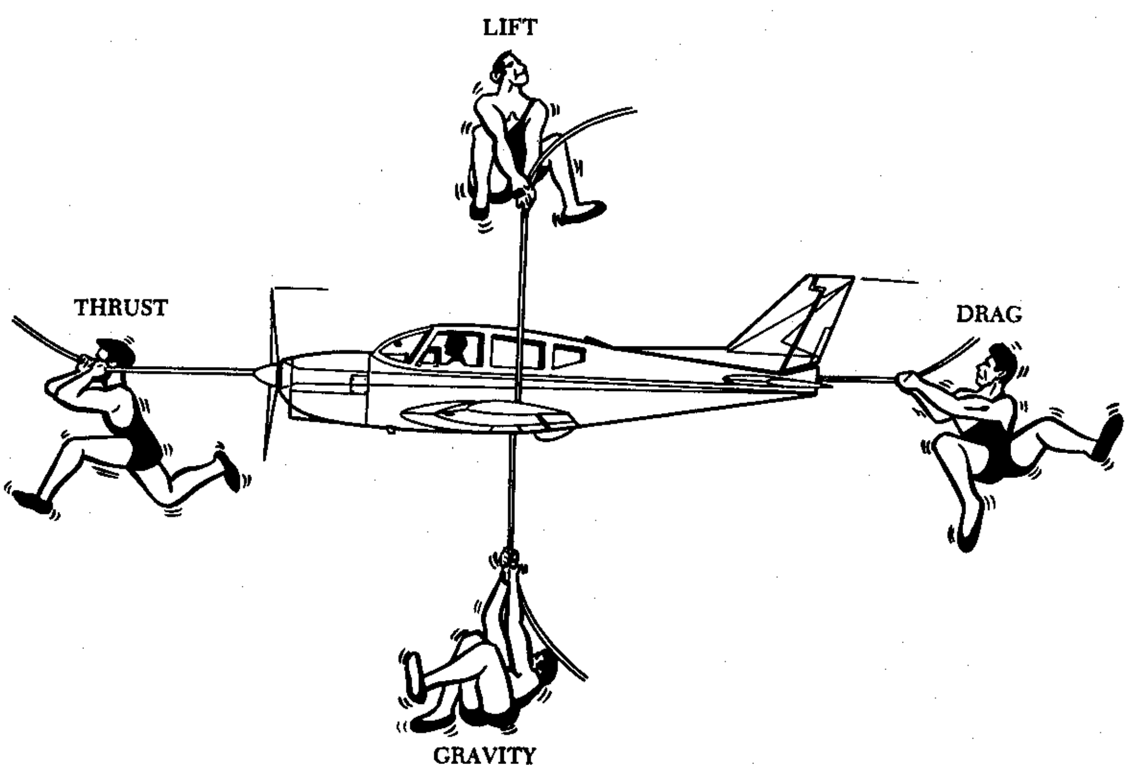


FIGURE 2–7. Forces in action in flight.

Weight is the force of gravity acting downward upon everything that goes into the aircraft, such as the aircraft itself, the crew, the fuel, and the cargo.

Lift acts vertically and by so doing counteracts the effects of weight.

Drag is a backward deterrent force and is caused by the disruption of the airflow by the wings, fuselage, and protruding objects.

Thrust produced by the powerplant is the forward force that overcomes the force of drag.

Notice that these four forces are only in perfect balance when the aircraft is in straight and level unaccelerated flight.

The force of lift and drag are the direct result of the relationship between the relative wind and the aircraft. The force of lift always acts perpendicular to the relative wind, and the force of drag always acts parallel to the relative wind and in the same direction. These forces are actually the components that produced a resultant lift force on the wing as shown in figure 2-8.

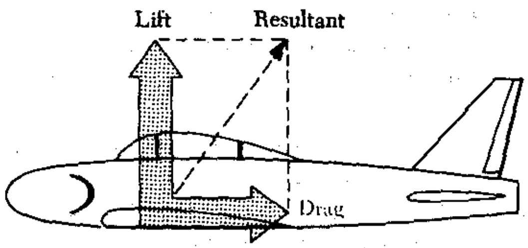


FIGURE 2-8. Resultant of lift and drag.

Weight has a definite relationship with lift, and thrust with drag. This relationship is quite simple, but very important in understanding the aerodynamics of flying. As stated previously, lift is the upward force on the wing acting perpendicular to the relative wind. Lift is required to counteract the aircraft's weight, caused by the force of gravity acting on the mass of the aircraft. This weight force acts downward through a point called the center of gravity which is the point at which all the weight of the aircraft is considered to be concentrated. When the lift force is in equilibrium with the weight force, the aircraft neither gains nor loses altitude. If lift becomes less than weight, the aircraft loses altitude. When the lift is greater than weight, the aircraft gains altitude.

Drag must be overcome in order for the aircraft to move, and movement is essential to obtain lift. To overcome the drag and move the aircraft forward, another force is essential. This force is thrust. Thrust is derived from jet propulsion or from a propeller and engine combination. Jet propulsion theory is based on Newton's third law of motion which states that for every action there is an equal and opposite reaction. For example, in firing a gun the action is the bullet going forward while the reaction is the gun recoiling backwards. The turbine engine causes a mass of air to be moved backward at high velocity causing a reaction forward that moves the aircraft.

In a propeller/engine combination, the propeller is actually two or more revolving airfoils mounted on a horizontal shaft. The motion of the blades through the air produces lift similar to the lift on the wing, but acts in a horizontal direction, pulling the aircraft forward.

Before the aircraft begins to move, thrust must be exerted. It continues to move and gain speed until thrust and drag are equal. In order to maintain a steady speed, thrust and drag must remain equal, just as lift and weight must be equal for steady, horizontal flight. We have seen that increasing the lift means that the aircraft moves upward, whereas decreasing the lift so that it is less than the weight causes the aircraft to lose altitude. A similar rule applies to the two forces of thrust and drag. If the r.p.m. of the engine is reduced, the thrust is lessened, and the aircraft slows down. As long as the thrust is less than the drag, the aircraft travels more and more slowly until its speed is insufficient to support it in the air.

Likewise, if the r.p.m. of the engine is increased, thrust becomes greater than drag, and the speed of the aircraft increases. As long as the thrust continues to be greater than the drag, the aircraft continues to accelerate. When drag equals thrust, the aircraft flies at a steady speed.

The relative motion of the air over an object that produces lift also produces drag. Drag is the resistance of the air to objects moving through it. If an aircraft is flying on a level course, the lift force acts vertically to support it while the drag force acts horizontally to hold it back. The total amount of drag on an aircraft is made up of many drag forces, but for our purposes, we will only consider three—***parasite drag, profile drag, and induced drag.***

Parasite drag is made up of a combination of many different drag forces. Any exposed object on an aircraft offers some resistance to the air, and the more objects in the airstream, the more parasite drag. While parasite drag can be reduced by reducing the number of exposed parts to as few as practical and streamlining their shape, skin friction is the type of parasite drag most difficult to reduce. No surface is perfectly smooth. Even machined surfaces when inspected under magnification have a ragged uneven appearance. These ragged surfaces deflect the air near the surface causing resistance to smooth airflow. Skin friction can be reduced by using glossy flat finishes and eliminating protruding rivet heads, roughness, and other irregularities.

Profile drag may be considered the parasite drag of the airfoil. The various components of parasite drag are all of the same nature as profile drag.

The action of the airfoil that gives us lift also causes induced drag. Remember that the pressure above the wing is less than atmospheric, and the pressure below the wing is equal to or greater than atmospheric pressure. Since fluids always move from high pressure toward low pressure, there is a spanwise movement of air from the bottom of the wing outward from the fuselage and upward around the wing tip. This flow of air results in "spillage" over the wing tip, thereby setting up a whirlpool of air called a vortex (figure 2–9). The air on the upper surface has a tendency to move in toward the fuselage and off the trailing edge. This air current forms a similar vortex at the inner portion of the trailing edge of the wing. These vortices increase drag, because of the turbulence produced, and constitute induced drag.

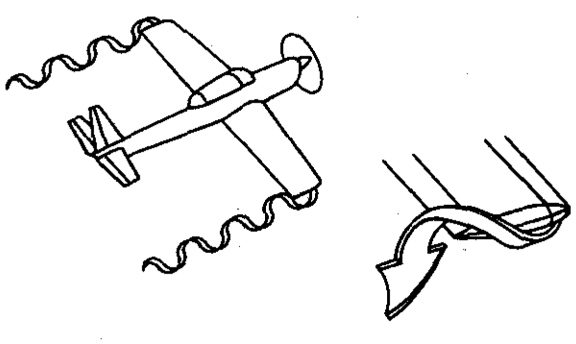


FIGURE 2–9. Wing tip vortices.

Just as lift increases with an increase in angle of attack, induced drag also increases as the angle of attack becomes greater. This occurs because as the angle of attack is increased, there is a greater pressure difference between the top and bottom of the wing. This causes more violent vortices to be set up, resulting in more turbulence and more induced drag.

AXES OF AN AIRCRAFT

Whenever an aircraft changes its attitude in flight, it must turn about one or more of three axes. Figure 2–10 shows the three axes, which are imaginary lines passing through the center of the aircraft. The axes of an aircraft can be considered as imaginary axles around which the aircraft turns like a wheel. At the center, where all three axes intersect, each is perpendicular to the other two. The axis which extends lengthwise through the fuselage from the nose to the tail is called the longitudinal axis. The axis which extends crosswise, from wing tip to wing tip, is the lateral axis. The axis which passes through the center, from top to bottom, is called the vertical axis.

Motion about the longitudinal axis resembles the roll of a ship from side to side. In fact, the names used in describing the motion about an aircraft's three axes were originally nautical terms. They have been adapted to aeronautical terminology because of the similarity of motion between an aircraft and a ship.

Thus, the motion about the longitudinal axis is called roll; motion along the lateral (crosswing) axis is called pitch. Finally, an aircraft moves about its vertical axis in a motion which is termed yaw. This is a horizontal movement of the nose of the aircraft.

Roll, pitch, and yaw—the motions an aircraft makes about its longitudinal, lateral, and vertical axes—are controlled by three control surfaces. Roll is produced by the ailerons, which are located at the trailing edges of the wings. Pitch is affected by the elevators, the rear portion of the horizontal tail assembly. Yaw is controlled by the rudder, the rear portion of the vertical tail assembly.

STABILITY AND CONTROL

An aircraft must have sufficient stability to maintain a uniform flight path and recover from the various upsetting forces. Also, to achieve the best performance, the aircraft must have the proper response to the movement of the controls.

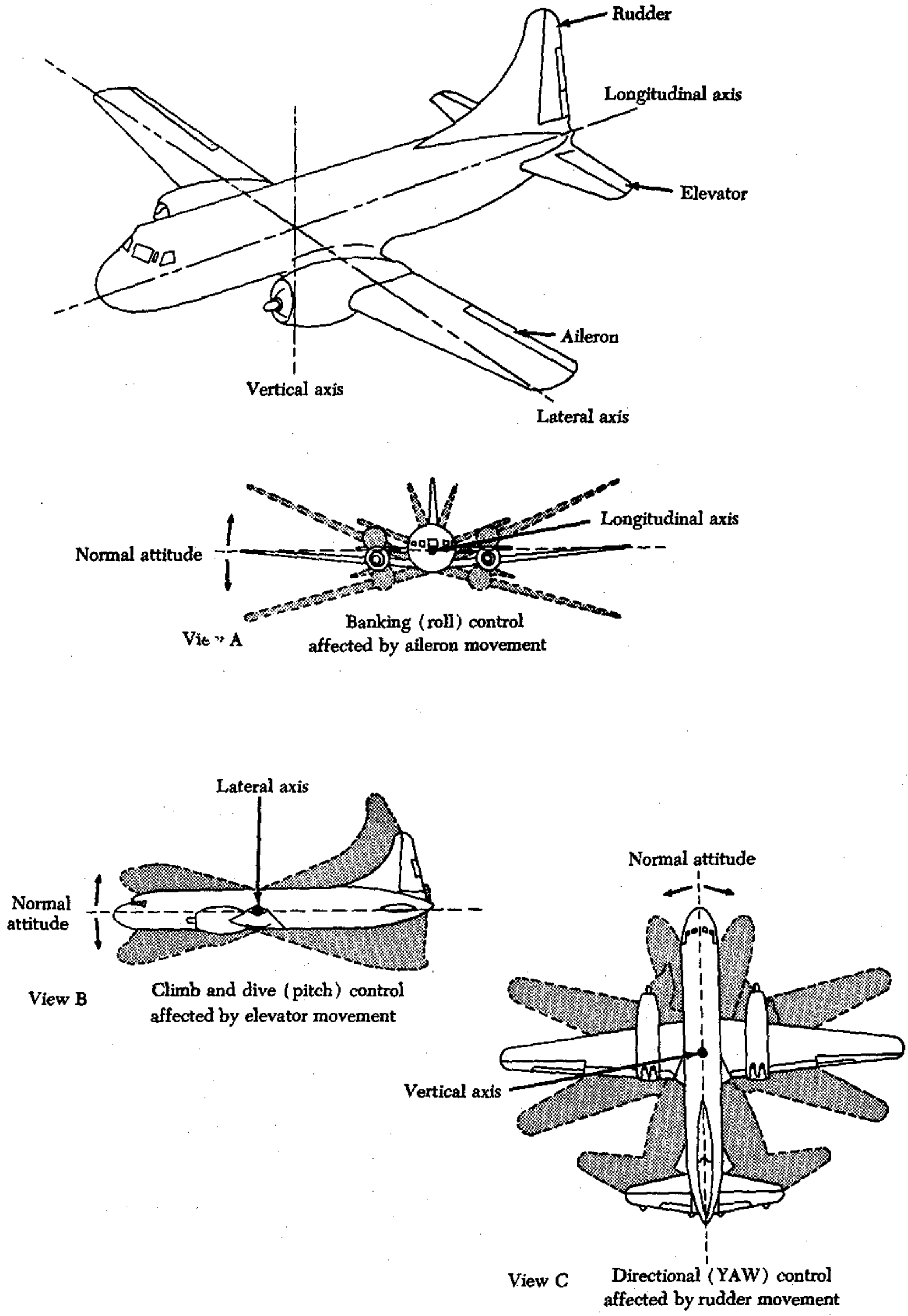


FIGURE 2–10. Motion of an aircraft about its axes.

Three terms that appear in any discussion of stability and control are: (1) Stability, (2) maneuverability, and (3) controllability. Stability is the characteristic of an aircraft which tends to cause it to fly (hands off) in a straight and level flight path. Maneuverability is the ability of an aircraft to be directed along a desired flight path and to withstand the stresses imposed. Controllability is the quality of the response of an aircraft to the pilot's commands while maneuvering the aircraft.

Static Stability

An aircraft is in a state of equilibrium when the sum of all the forces acting on the aircraft and all the moments is equal to zero. An aircraft in equilibrium experiences no accelerations, and the aircraft continues in a steady condition of flight. A gust of wind or a deflection of the controls disturbs the equilibrium, and the aircraft experiences acceleration due to the unbalance of moment or force.

The three types of static stability are defined by the character of movement following some disturbance from equilibrium. Positive static stability exists when the disturbed object tends to return to equilibrium. Negative static stability or static instability exists when the disturbed object tends to continue in the direction of disturbance. Neutral static stability exists when the disturbed object has neither the tendency to return nor continue in the displacement direction, but remains in equilibrium in the direction of disturbance. These three types of stability are illustrated in figure 2–11.

Dynamic Stability

While static stability deals with the tendency of a displaced body to return to equilibrium, dynamic stability deals with the resulting motion with time. If an object is disturbed from equilibrium, the time history of the resulting motion defines the dynamic stability of the object. In general, an object demonstrates positive dynamic stability if the amplitude of motion decreases with time. If the amplitude of motion increases with time, the object is said to possess dynamic instability.

Any aircraft must demonstrate the required degrees of static and dynamic stability. If an aircraft were designed with static instability and a rapid rate of dynamic instability, the aircraft would be very difficult, if not impossible, to fly. Usually, positive dynamic stability is required in an aircraft design to prevent objectionable continued oscillations of the aircraft.

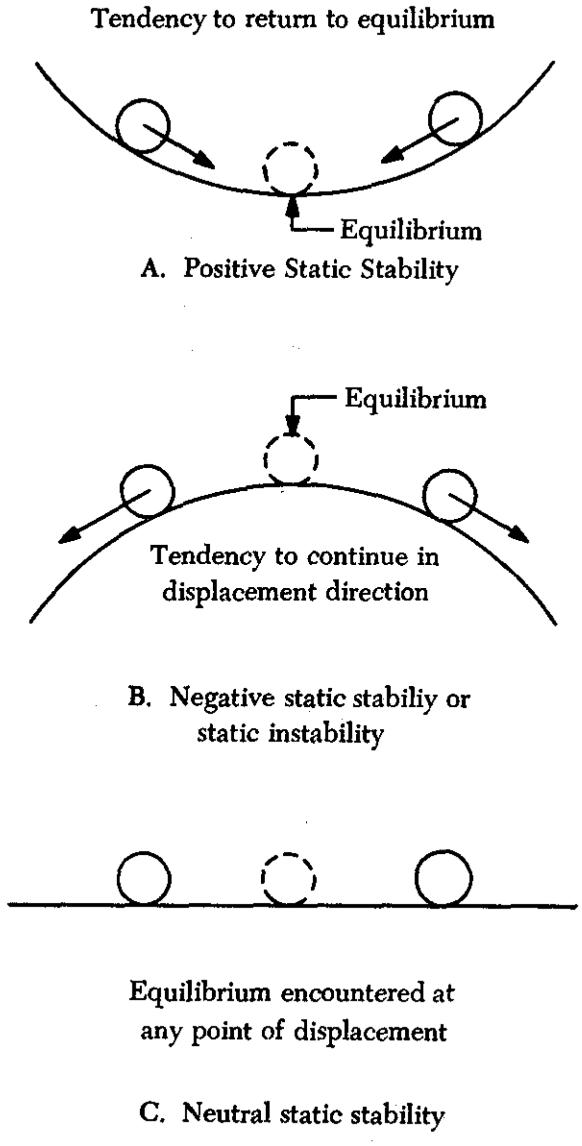


FIGURE 2–11. Static stability.

Longitudinal Stability

When an aircraft has a tendency to keep a constant angle of attack with reference to the relative wind—that is, when it does not tend to put its nose down and dive or lift its nose and stall—it is said to have longitudinal stability. Longitudinal stability refers to motion in pitch. The horizontal stabilizer is the primary surface which controls longitudinal stability. The action of the stabilizer depends upon the speed and angle of attack of the aircraft.

Figure 2–12 illustrates the contribution of tail lift to stability. If the aircraft changes its angle of attack, a change in lift takes place at the aerodynamic center (center of pressure) of the horizontal stabilizer.

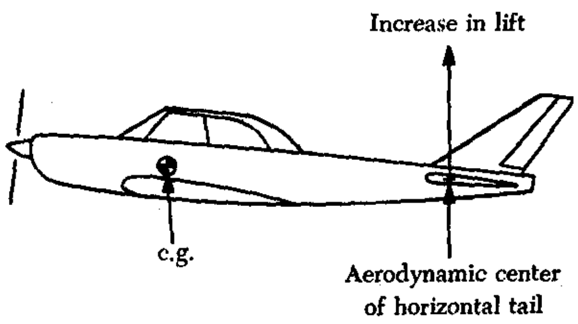


FIGURE 2-12. Producing tail lift.

Under certain conditions of speed, load, and angle of attack, the flow of air over the horizontal stabilizer creates a force which pushes the tail up or down. When conditions are such that the airflow creates equal forces up and down, the forces are said to be in equilibrium. This condition is usually found in level flight in calm air.

Directional Stability

Stability about the vertical axis is referred to as directional stability. The aircraft should be designed so that when it is in straight and level flight it remains on its course heading even though the pilot takes his hands and feet off the controls. If an aircraft recovers automatically from a skid, it has been well designed and possesses good directional balance. The vertical stabilizer is the primary surface which controls directional stability.

As shown in figure 2-13, when an aircraft is in a sideslip or yawing, the vertical tail experiences a change in angle of attack with a resulting change in lift [not to be confused with the lift created by the wing]. The change in lift, or side force, on the vertical tail creates a yawing moment about the center of gravity which tends to return the aircraft to its original flight path.

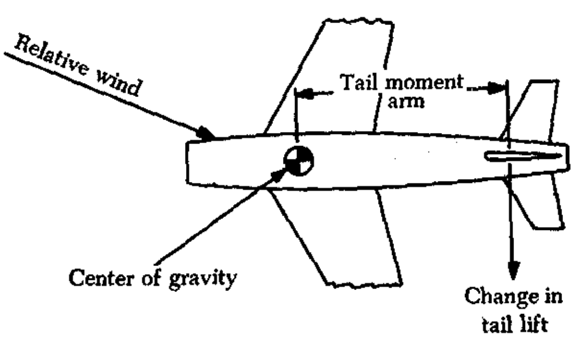


FIGURE 2-13. Contribution of vertical tail to directional stability.

Sweptback wings aid in directional stability. If the aircraft yaws from its direction of flight, the wing which is farther ahead offers more drag than the wing which is aft. The effect of this drag is to hold back the wing which is farther ahead, and to let the other wing catch up.

Directional stability is also aided by using a large dorsal fin and a long fuselage.

The high Mach numbers of supersonic flight reduce the contribution of the vertical tail to directional stability. To produce the required directional stability at high Mach numbers, a very large vertical tail area may be necessary. Ventral (belly) fins may be added as an additional contribution to directional stability.

Lateral Stability

We have seen that pitching is motion about the aircraft's lateral axis and yawing is motion about its vertical axis. Motion about its longitudinal (fore and aft) axis is a lateral or rolling motion. The tendency to return to the original attitude from such motion is called lateral stability.

The lateral stability of an airplane involves consideration of rolling moments due to sideslip. A sideslip tends to produce both a rolling and a yawing motion. If an airplane has a favorable rolling moment, a sideslip will tend to return the airplane to a level flight attitude.

The principal surface contributing to the lateral stability of an airplane is the wing. The effect of the geometric dihedral (figure 2-14) of a wing is a powerful contribution to lateral stability. As shown in figure 2-14, a wing with dihedral develops stable rolling moments with sideslip. With the relative wind from the side, the wing into the wind is subject to an increase in angle of attack and develops an increase in lift. The wing away from the wind is subject to a decrease in angle of attack and develops less lift. The changes in lift effect a rolling moment tending to raise the windward wing.

When a wing is swept back, the effective dihedral increases rapidly with a change in the lift coefficient of the wing. Sweepback is the angle between a line perpendicular to the fuslage center line and the quarter chord of each wing airfoil section. Sweepback in combination with dihedral causes the dihedral effect to be excessive. As shown in figure 2-15, the swept-wing aircraft in a sideslip has the wing that is into the wind operating with an effective decrease in sweepback, while the wing out of the wind is operating with an effective increase in

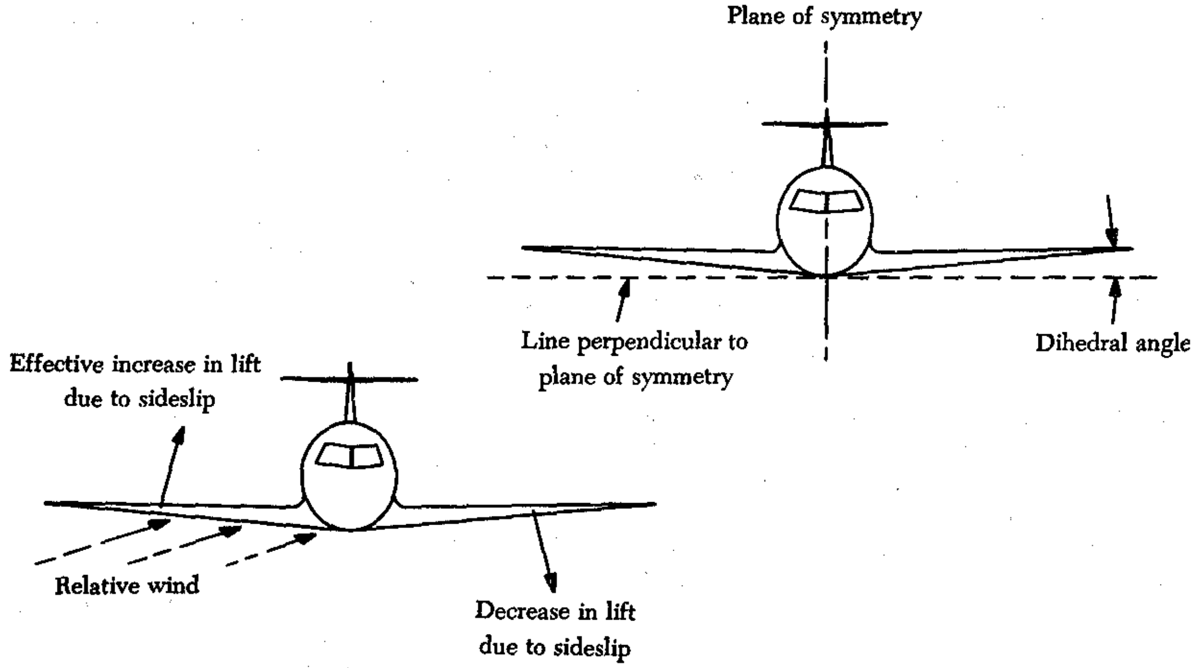


FIGURE 2–14. Contribution of dihedral to lateral stability.

sweepback. The wing into the wind develops more lift, and the wing out of the wind develops less. This tends to restore the aircraft to a level flight attitude.

The amount of effective dihedral necessary to produce satisfactory flying qualities varies greatly with the type and purpose of the aircraft. Generally, the effective dihedral is kept low, since high roll due to sideslip can create problems. Excessive dihedral effect can lead to Dutch Roll, difficult rudder coordination in rolling maneuvers, or place extreme demands for lateral control power during crosswind takeoff and landing.

CONTROL

Control is the action taken to make the aircraft follow any desired flight path. When an aircraft is said to be controllable, it means that the craft responds easily and promptly to movement of the controls. Different control surfaces are used to control the aircraft about each of the three axes. Moving the control surfaces on an aircraft changes the airflow over the aircraft's surface. This, in turn, creates changes in the balance of forces acting to keep the aircraft flying straight and level.

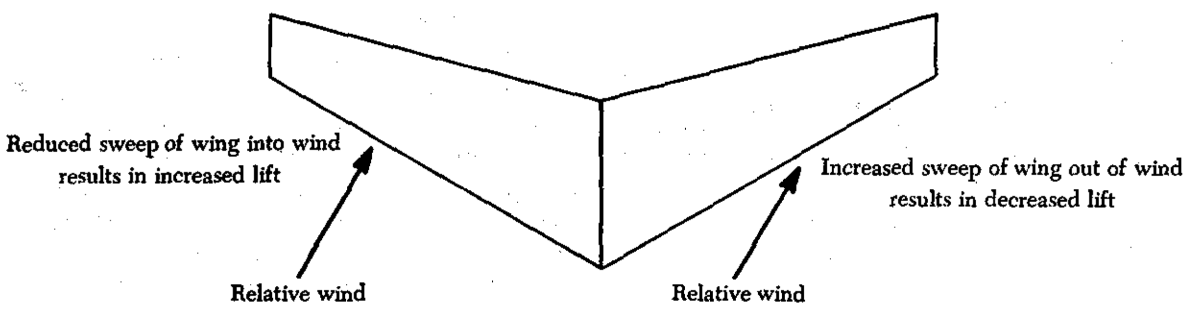


FIGURE 2–15. Effect of sweepback on lateral stability.

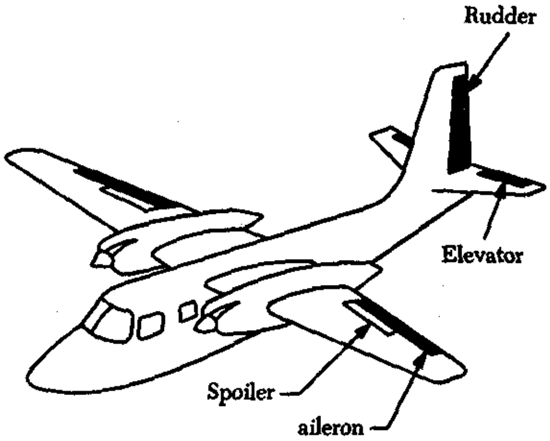


FIGURE 2-16. Primary flight controls.

FLIGHT CONTROL SURFACES

The flight control surfaces are hinged or movable airfoils designed to change the attitude of the aircraft during flight. These surfaces may be divided into three groups, usually referred to as the primary group, secondary group, and auxiliary group.

Primary Group

The primary group includes the ailerons, elevators, and rudder (figure 2-16). These surfaces are used for moving the aircraft about its three axes.

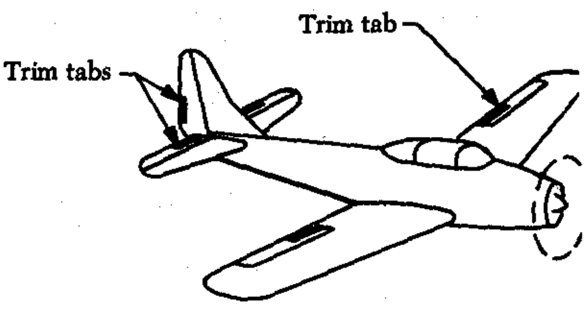


FIGURE 2-17. Trim tabs.

The ailerons and elevators are generally operated from the cockpit by a control stick on single-engine aircraft and by a wheel and yoke assembly on multiengine aircraft. The rudder is operated by foot pedals on all types of aircraft.

Secondary Group

Included in the secondary group are the trim tabs and spring tabs. Trim tabs (figure 2-17) are small airfoils recessed into the trailing edges of the primary control surfaces. The purpose of trim tabs is to enable the pilot to trim out any unbalanced condition which may exist during flight, without exerting any pressure on the primary controls. Each trim tab is hinged to its parent primary control surface, but is operated by an independent control.

Spring tabs are similar in appearance to trim tabs, but serve an entirely different purpose. Spring tabs are used to aid the pilot in moving the primary control surfaces.

Auxiliary Group

Included in the auxiliary group of flight control surfaces are the wing flaps, spoilers, speed brakes, slats, leading edge flaps and slots.

The auxiliary groups may be divided into two sub-groups. Those whose primary purpose is lift augmenting and those whose primary purpose is lift decreasing. In the first group are the flaps, both trailing edge and leading edge (slats), and slots. The lift decreasing devices are speed brakes and spoilers.

The trailing edge airfoils (flaps) increase the wing area thereby increasing lift on takeoff and decrease the speed during landing. These airfoils are retractable and fair into the wing contour. Others are simply a portion of the lower skin which extends into the airstream thereby slowing the aircraft.

Leading edge flaps are airfoils extended from and retracted into the leading edge of the wing. Some installations create a slot (an opening between the extended airfoil and the leading edge). The flap (termed slat by some manufacturers) and slot create additional lift at the slower speeds of takeoff and landing. Other installations have permanent slots built in the leading edge of the wing. At cruising speeds, the trailing edge and leading edge flaps (slats) are retracted into the wing proper.

Lift decreasing devices are the speed brakes (spoilers). In some installations, there are two types of spoilers. The ground spoiler is extended only after the aircraft is on the ground thereby assisting in the braking action. The flight spoiler assists in lateral control by being extended whenever the aileron on that wing is rotated up. When actuated as speed brakes, the spoiler panels on both wings raise up—the panel on the "up" aileron wing raising more than the panel on the down aileron side. This provides speed brake operation and later control simultaneously.

Slats are movable control surfaces attached to the leading edges of the wings. When the slat is closed, it forms the leading edge of the wing. When in the open position (extended forward), a slot is created between the slat and the wing leading edge. At low airspeeds this increases lift and improves handling characteristics, allowing the aircraft to be controlled at airspeeds below the otherwise normal landing speed.

CONTROL AROUND THE LONGITUDINAL AXIS

The motion of the aircraft about the longitudinal axis is called rolling or banking. The ailerons (figure 2–18) are used to control this movement. The ailerons form a part of the wing and are located in the trailing edge of the wing toward the tips. Ailerons are the movable surfaces of an otherwise fixed-surface wing. The aileron is in neutral position when it is streamlined with the trailing edge of the wing.

Ailerons respond to side pressure applied to the control stick. Pressure applied to move the stick toward the right raises the right aileron and lowers the left aileron, causing the aircraft to bank to the right. Ailerons are linked together by control cables so that when one aileron is down, the opposite aileron is up. The function of the lowered aileron is to increase the lift by increasing the wing camber. At the same time, the down aileron also creates some additional drag since it is in the area of high pressure below the wing. The up aileron, on the opposite end of the wing, decreases lift on that end of the wing. The increased lift on the wing whose aileron is down, raises this wing. This causes the aircraft to roll about its longitudinal axis as shown in figure 2–19.

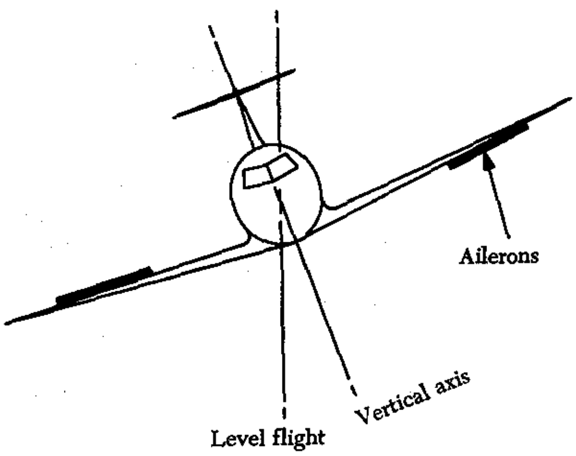


FIGURE 2–18. Aileron action.

As a result of the increased lift on the wing with the lowered aileron, drag is also increased. This drag attempts to pull the nose in the direction of the high wing. Since the ailerons are used with the rudder when making turns, the increased drag tries to turn the aircraft in the direction opposite to that desired. To avoid this undesirable effect, aircraft are often designed with differential travel of the ailerons.

Differential aileron travel (figure 2–20) provides more aileron up travel than down travel for a given movement of the control stick or wheel in the cockpit.

The spoilers, or speed brakes as they are also called, are plates fitted to the upper surface of the wing. They are usually deflected upward by hydraulic actuators in response to control wheel movement in the cockpit. The purpose of the spoilers is to disturb the smooth airflow across the top of the airfoil thereby creating an increased amount of drag and a decreased amount of lift on that airfoil.

Spoilers are used primarily for lateral control. When banking the airplane, the spoilers function with the ailerons. The spoilers on the up aileron side raise with that aileron to further decrease the lift on that wing. The spoiler on the opposite side remains in the faired position. When the spoilers are used as a speed brake, they are all deflected upward simultaneously. A separate control lever is provided for operating the spoilers as speed brakes.

While we tend to think of a spoiler as being a fairly complicated, controlled device, we should keep in mind that some are not controllable. Some spoilers are automatic in operation in that they come into effect only at a high angle of attack. This

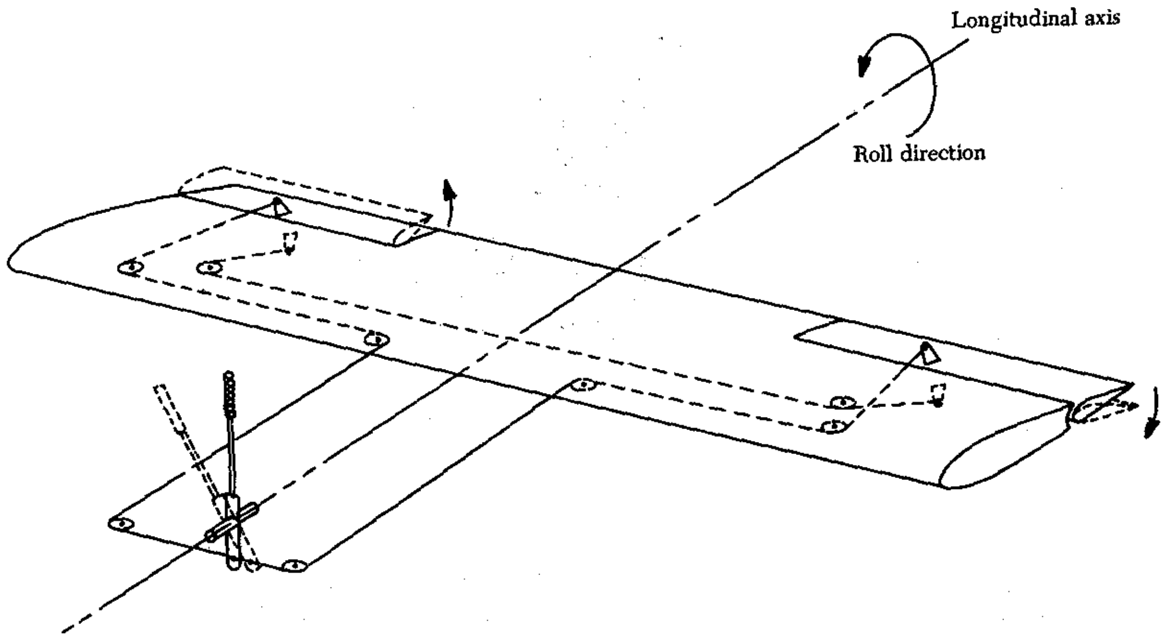


FIGURE 2–19. Aileron control system.

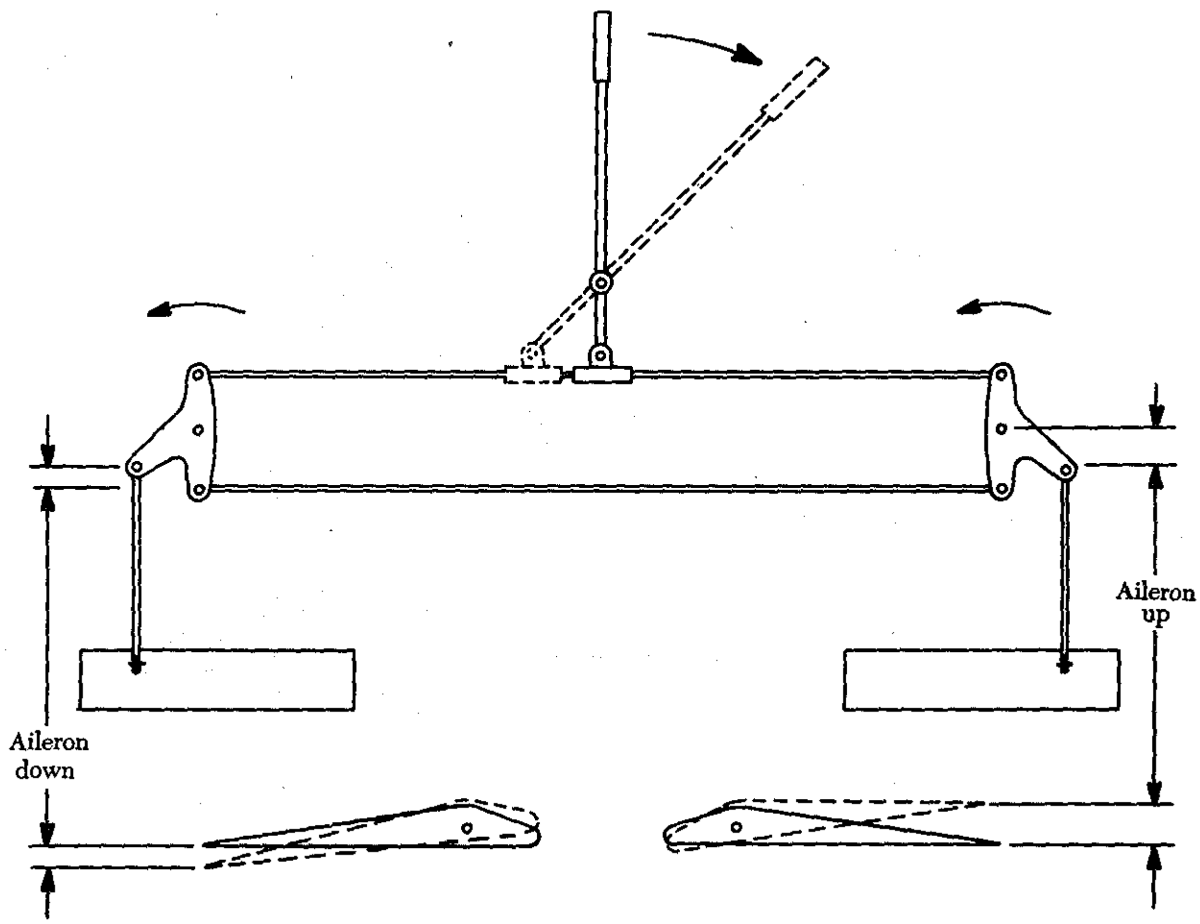


FIGURE 2–20. Aileron differential control.

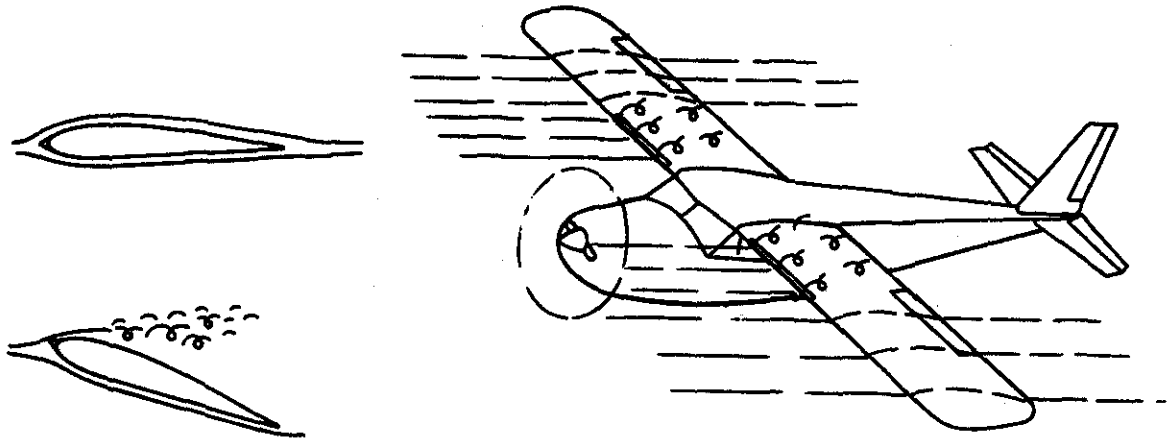


FIGURE 2-21. Fixed spoilers or stall strip.

arrangement keeps them out of the slipstream at cruise and high speeds.

A fixed spoiler may be a small wedge affixed to the leading edge of the airfoil as shown in figure 2-21. This type spoiler causes the inboard portion of the wing to stall ahead of the outboard portion which results in aileron control right up to the occurrence of complete wing stall.

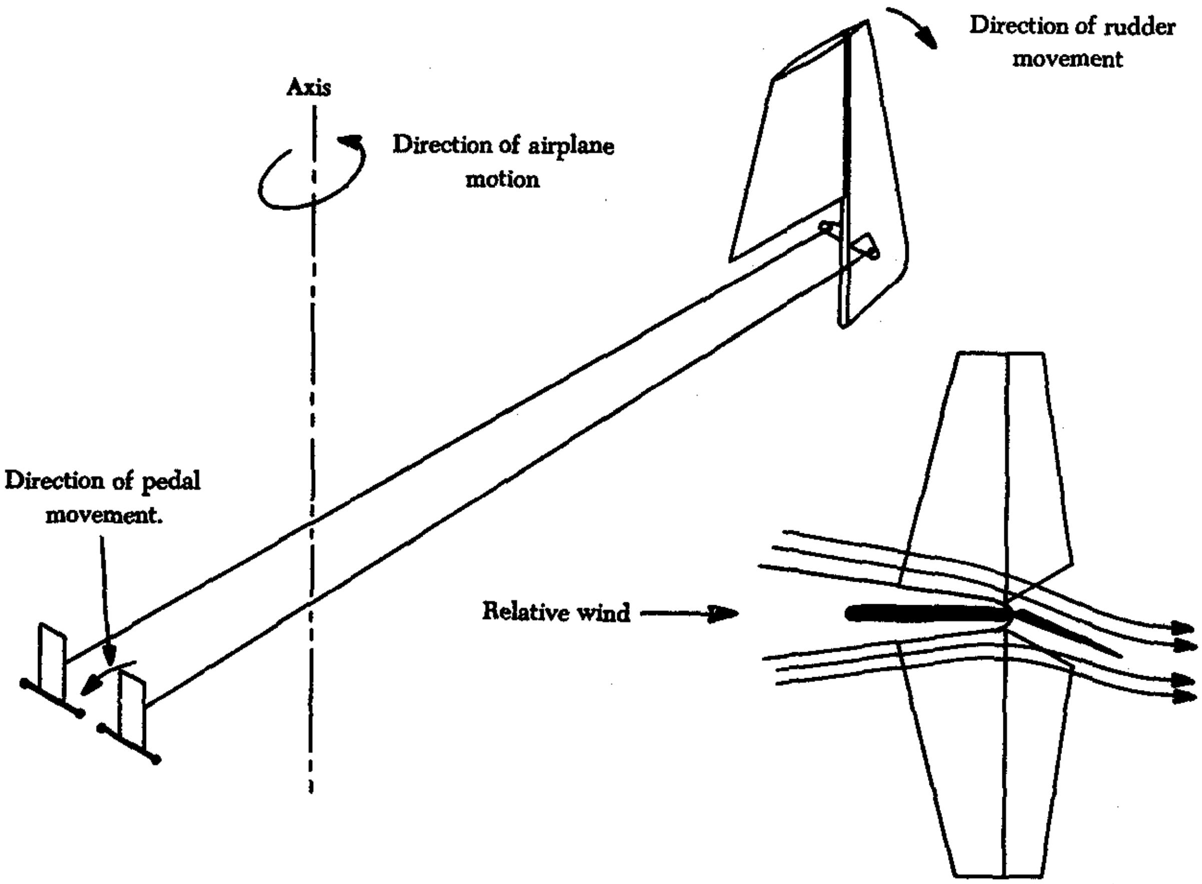


FIGURE 2-22. Rudder action.

Use extreme accuracy in positioning leading edge spoilers when re-installing them after they have been removed for maintenance. Improper positioning may result in adverse stall characteristics. Always follow the manufacturers' instructions regarding location and method of attachment.

CONTROL AROUND THE VERTICAL AXIS

Turning the nose of the aircraft causes the aircraft to rotate about its vertical axis. Rotation of the aircraft about the vertical axis is called yawing. This motion is controlled by using the rudder as illustrated in figure 2–22.

The rudder is a movable control surface attached to the trailing edge of the vertical stabilizer. To turn the aircraft to the right, the rudder is moved to the right. The rudder protrudes into the airstream, causing a force to act upon it. This is the force necessary to give a turning movement about the center of gravity which turns the aircraft to the right. If the rudder is moved to the left, it induces a counterclockwise rotation and the aircraft similarly turns to the left. The rudder can also be used in controlling a bank or turn in flight.

The main function of the rudder is to turn the aircraft in flight. This turn is maintained by the side pressure of the air moving past the vertical surfaces. When an aircraft begins to slip or skid, rudder pressure is applied to keep the aircraft headed in the desired direction (balanced).

Slip or sideslipping refers to any motion of the aircraft to the side and downward toward the inside of a turn. Skid or skidding refers to any movement upward and outward away from the center of a turn.

CONTROL AROUND THE LATERAL AXIS

When the nose of an aircraft is raised or lowered, it is rotated about its lateral axis. Elevators are the movable control surfaces that cause this rotation (figure 2–23). They are normally hinged to the trailing edge of the horizontal stabilizer.

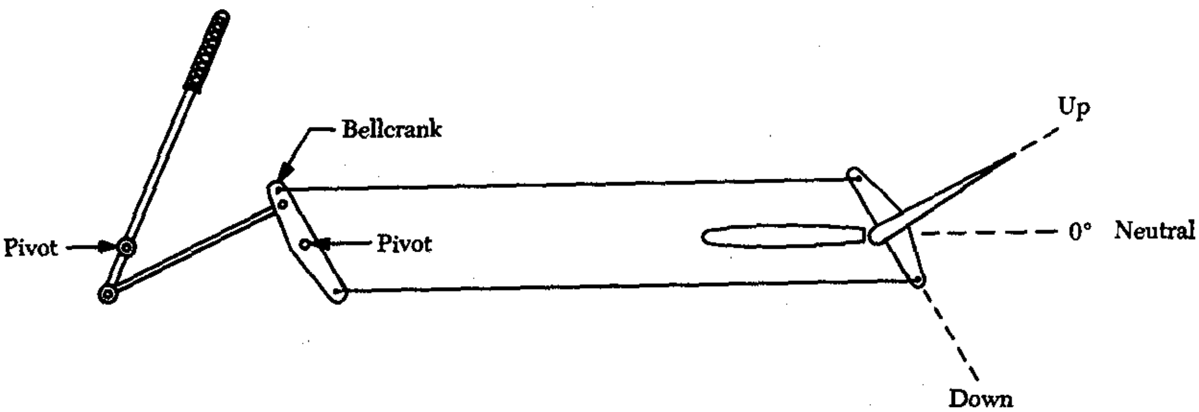


FIGURE 2–23. Elevator action.

The elevators are used to make the aircraft climb or dive and also to obtain sufficient lift from the wings to keep the aircraft in level flight at various speeds.

The elevators can be moved either up or down. If the elevator is rotated up, it decreases the lift force on the tail causing the tail to lower and the nose to rise. If the elevator is rotated downward, it increases the lift force on the tail causing it to rise and the nose to lower. Lowering the aircraft's nose increases forward speed, and raising the nose decreases forward speed.

Some aircraft use a movable horizontal surface called a stabilator (figure 2–24). The stabilator serves the same purpose as the horizontal stabilizer and elevator combined. When the cockpit control is moved, the complete stabilator is moved to raise or lower the leading edge, thus changing the angle of attack and the amount of lift on the tail surfaces.

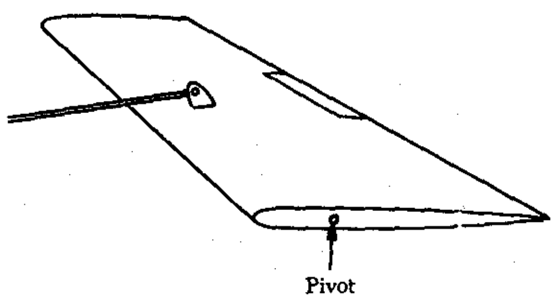


FIGURE 2–24. Movable horizontal stabilator.

Aircraft empennages have been designed which combine the vertical and horizontal stabilizers. Such empennages have the stabilizers set at an angle as shown in figure 2-25. This arrangement is referred to as a butterfly or vee tail.

The control surfaces are hinged to the stabilizers at the trailing edges. The stabilizing portion of this arrangement is called a stabilator, and the control portion is called the ruddervator. The ruddervators can be operated both up or both down at the same time. When used in this manner, the result is the same as with any other type of elevator. This action is controlled by the stick or control column.

The ruddervators can be made to move opposite each other by pushing the left or right rudder pedal (figure 2-26). If the right rudder padel is pushed, the right ruddervator moves down and the left ruddervator moves up. This produces turning moments to move the nose of the aircraft to the right.

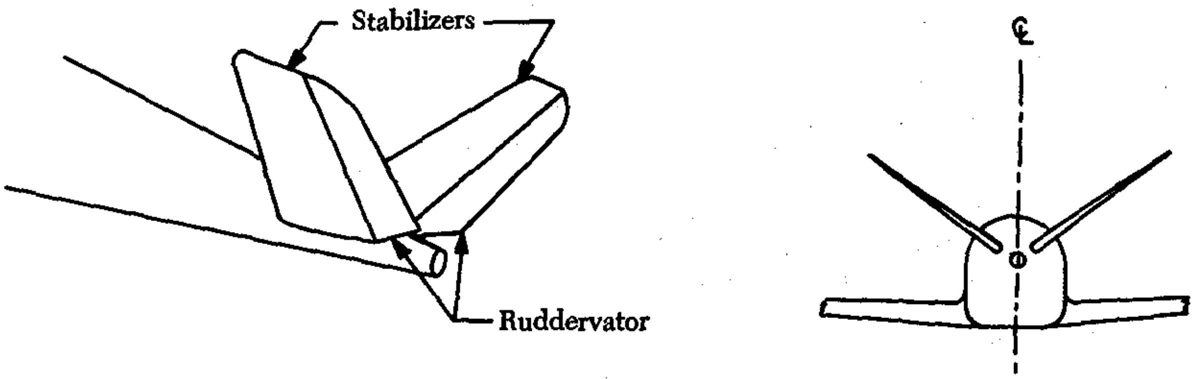


FIGURE 2-25. A butterfly or vee tail.

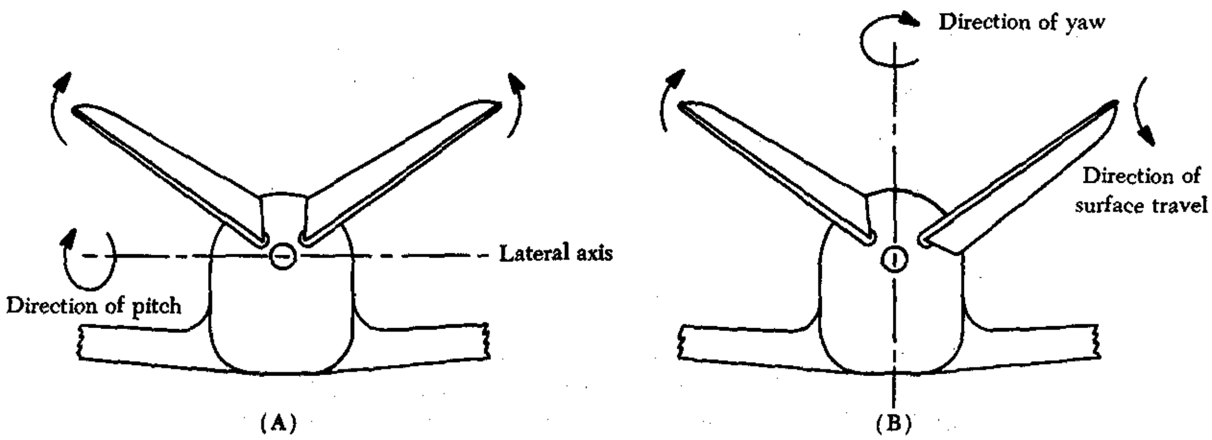


FIGURE 2-26. Ruddervator action. (A) functioning as an elevator; (B) functioning as a rudder.

TABS

Even though an aircraft has inherent stability, it does not always tend to fly straight and level. The weight of the load and its distribution affect stability. Various speeds also affect its flight characteristics. If the fuel in one wing tank is used before that in the other wing tank, the aircraft tends to roll toward the full tank. All of these variations require constant exertion of pressure on the controls for correction. While climbing or gliding, it is necessary to apply pressure on the controls to keep the aircraft in the desired attitude.

To offset the forces that tend to unbalance an aircraft in flight, ailerons, elevators, and rudders are provided with auxiliary controls known as tabs. These are small, hinged control surfaces (figure 2-27) attached to the trailing edge of the primary control surfaces. Tabs can be moved up or down by means of a crank or moved electrically from the cockpit. These tabs can be used to balance the forces on the controls so that the aircraft flies straight and level, or may be set so that the aircraft maintains either a climbing or gliding attitude.

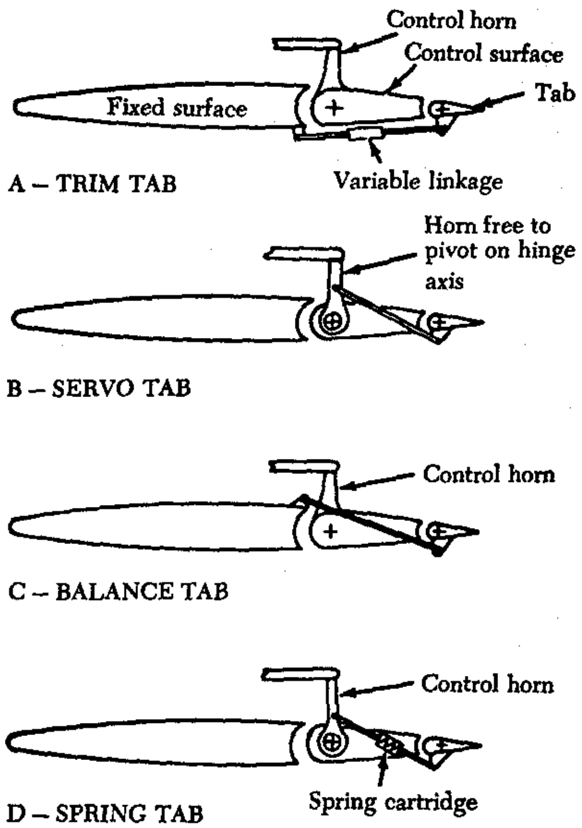


FIGURE 2–27. Flight control trim tab types.

Trim Tabs

Trim tabs trim the aircraft in flight. To trim means to correct any tendency of the aircraft to move toward an undesirable flight attitude. Trim tabs control the balance of an aircraft so that it maintains straight and level flight without pressure on the control column, control wheel, or rudder pedals. Figure 2–27A illustrates a trim tab. Note that the tab has a variable linkage which is adjustable from the cockpit. Movement of the tab in one direction causes a deflection of the control surface in the opposite direction. Most of the trim tabs installed on aircraft are mechanically operated from the cockpit through an individual cable system. However, some aircraft have trim tabs that are operated by an electrical actuator. Trim tabs are either controlled from the cockpit or adjusted on the ground before taking off. Trim tabs are installed on elevators, rudders, and ailerons.

Servo Tabs

Servo tabs (figure 2–27B) are very similar in operation and appearance to the trim tabs just discussed. Servo tabs, sometimes referred to as flight tabs, are used primarily on the large main control surfaces. They aid in moving the control surface and holding it in the desired position. Only the servo tab moves in response to movement of the cockpit control. (The servo tab horn is free to pivot to the main control surface hinge axis.) The force of the airflow on the servo tab then moves the primary control surface. With the use of a servo tab less force is needed to move the main control surface.

Balance Tabs

A balance tab is shown in figure 2–27C. The linkage is designed in such a way that when the main control surface is moved, the tab moves in the opposite direction. Thus, aerodynamic forces, acting on the tab, assist in moving the main control surface.

Spring Tabs

Spring tabs (figure 2–27D) are similar in appearance to trim tabs, but serve an entirely different purpose. Spring tabs are used for the same purpose as hydraulic actuators; that is, to aid in moving a primary control surface. There are various spring arrangements used in the linkage of the spring tab.

On some aircraft, a spring tab is hinged to the trailing edge of each aileron and is actuated by a spring-loaded push-pull rod assembly which is also linked to the aileron control linkage. The linkage is connected in such a way that movement of the aileron in one direction causes the spring tab to be deflected in the opposite direction. This provides a balanced condition, thus reducing the amount of force required to move the ailerons.

The deflection of the spring tabs is directly proportional to the aerodynamic load imposed upon the aileron; therefore, at low speeds the spring tab remains in a neutral position and the aileron is a direct manually controlled surface. At high speeds, however, where the aerodynamic load is great, the tab functions as an aid in moving the primary control surface.

To lessen the force required to operate the control surfaces they are usually balanced statically and aerodynamically. Aerodynamic balance is usually achieved by extending a portion of the con-

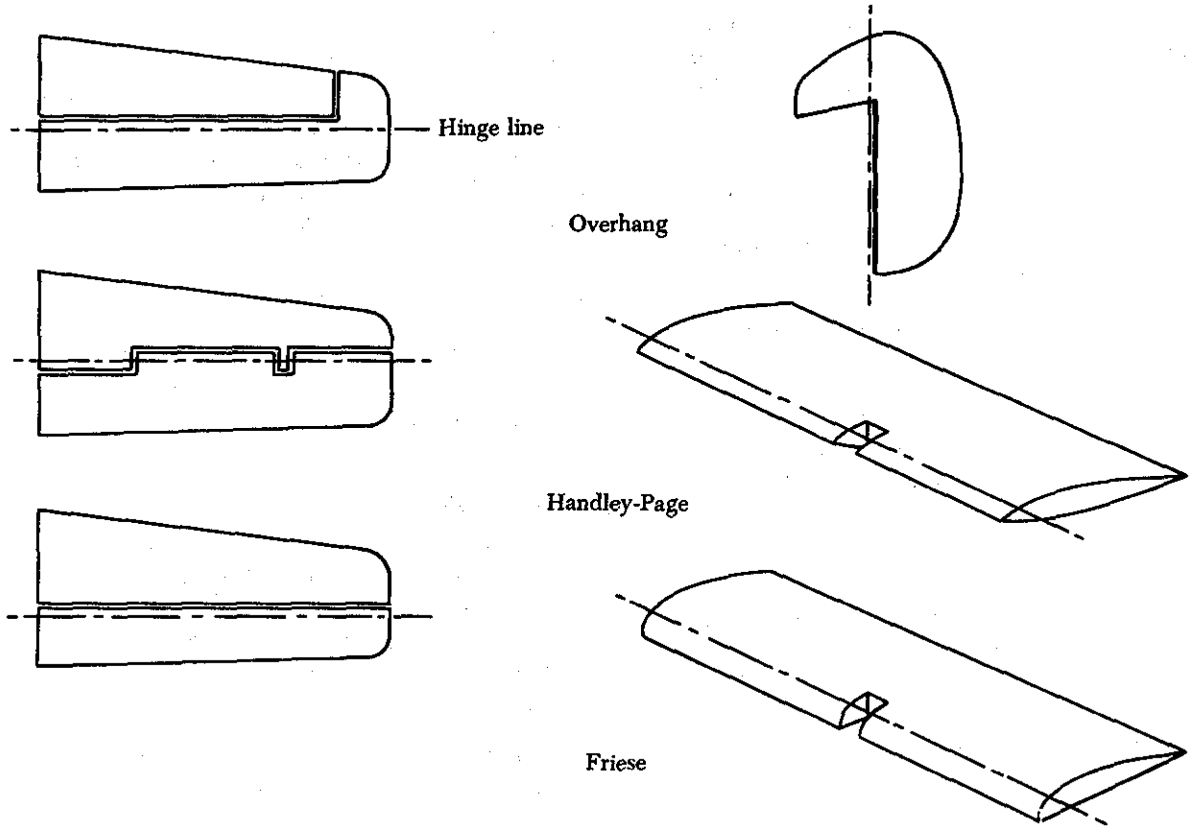


FIGURE 2–28. Three forms of aerodynamic balance.

trol surface ahead of the hinge line. This utilizes the airflow about the aircraft to aid in moving the surface. The various methods of achieving aerodynamic balance are shown in figure 2–28.

Static balance is accomplished by adding weight to the section forward of the hinge line until it weighs the same as the section aft of it. When repairing a control surface use care to prevent upsetting or disturbing the static balance. An unbalanced surface has a tendency to flutter as air passes over it.

High-Lift Devices

High-lift devices are used in combination with airfoils in order to reduce the takeoff or landing speed by changing the lift characteristics of an airfoil during the landing or takeoff phases. When these devices are no longer needed they are returned to a position within the wing to regain the normal characteristics of the airfoil.

Two high-lift devices commonly used on aircraft are shown in figure 2–29. One of these is known as a slot, and is used as a passageway through the leading edge of the wing. At high angles of attack the air flows through the slot and smooths out the airflow over the top surface of the wing. This enables the wing to pass beyond its normal stalling point without stalling. Greater lift is obtained with the wing operating at the higher angle of attack.

The other high-lift device is known as a flap. It is a hinged surface on the trailing edge of the wing. The flap is controlled from the cockpit, and when not in use fits smoothly into the lower surface of each wing. The use of flaps increases the camber of a wing and therefore the lift of the wing, making it possible for the speed of the aircraft to be decreased without stalling. This also permits a steeper gliding angle to be obtained as in the landing approach. Flaps are primarily used during takeoff and landing.

The types of flaps in use on aircraft include: (1) Plain, (2) split, (3) Fowler, and (4) slotted. The plain (figure 2–30) is simply hinged to the wing and forms a part of the wing surface when raised.

The split flap (figure 2–30) gets its name from the hinge at the bottom part of the wing near the trailing edge permitting it to be lowered from the

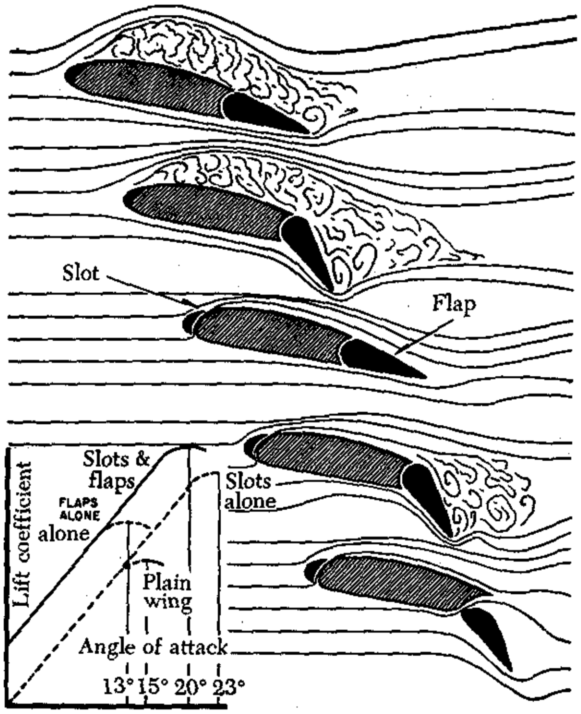


FIGURE 2–29. High-lift devices.

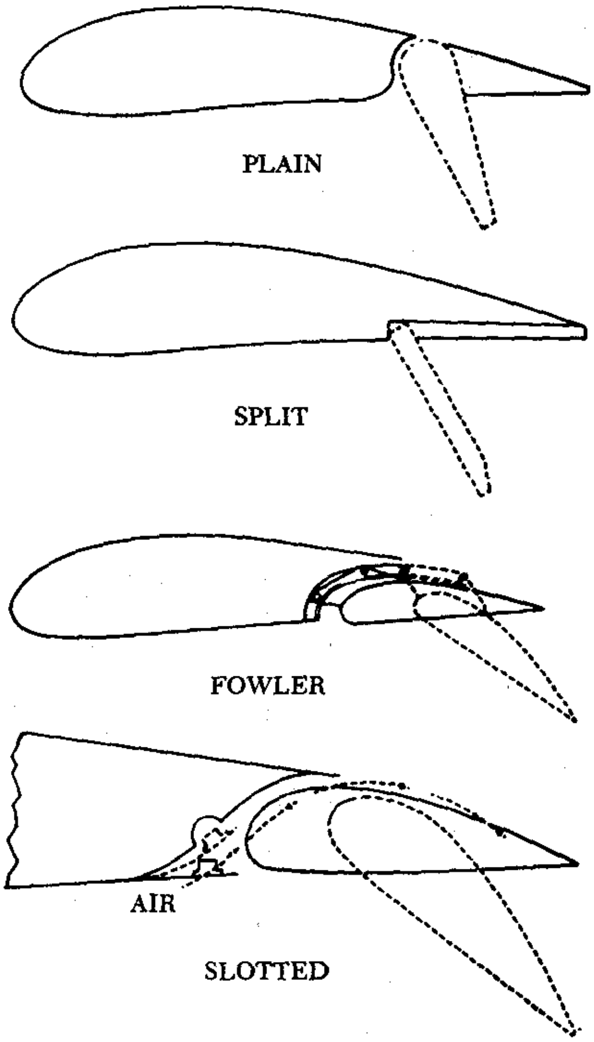


FIGURE 2–30. Types of wing flaps.

fixed top surface. The Fowler flap (figure 2–30) fits into the lower part of the wing so that it is flush with the surface. When the flap is operated, it slides backward on tracks and tilts downward at the same time. This increases wing camber, as do the other types of flaps. However, Fowler flaps also increase the wing area; thus, they provide added lift without unduly increasing drag.

The slotted flap (figure 2–30) is like the Fowler flap in operation, but in appearance it is similar to the plain flap. This flap is equipped with either tracks and rollers or hinges of a special design. During operation, the flap moves downward and rearward away from the position of the wing. The "slot" thus opened allows a flow of air over the upper surface of the flap. The effect is to streamline the airflow and to improve the efficiency of the flap.

BOUNDARY LAYER CONTROL DEVICES

The layer of air over the surface which is slower moving in relation to the rest of the slipstream is called the boundary layer. The initial airflow on a smooth surface (figure 2–31) gives evidence of a very thin boundary layer with the flow occurring in smooth laminations of air sliding smoothly over one another. Therefore, the term for this type of flow is the laminar boundary layer.

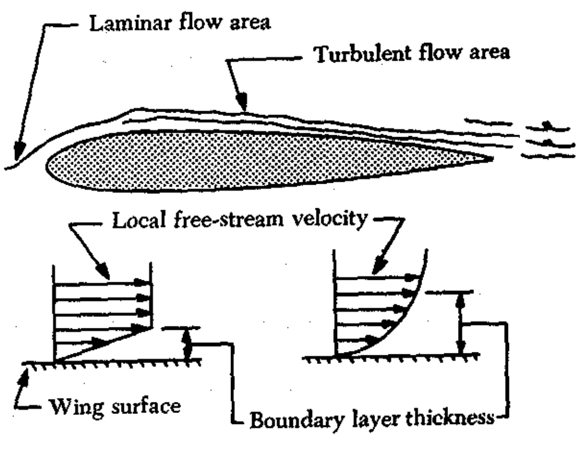


FIGURE 2–31. Boundary layer characteristics.

As the flow continues back from the leading edge, friction forces in the boundary layer continue to

dissipate the energy of the airstream, slowing it down. The laminar boundary layer increases in thickness with increased distance from the wing leading edge. Some distance back from the leading edge, the laminar flow begins an oscillatory disturbance which is unstable. A waviness occurs in the laminar boundary layer which ultimately grows larger and more severe and destroys the smooth laminar flow. Thus, a transition takes place in which the laminar boundary layer decays into a turbulent boundary layer. The same sort of transition can be noticed in the smoke from a cigarette in still air. At first, the smoke ribbon is smooth and laminar, then develops a definite waviness, and decays into a random turbulent smoke pattern.

Boundary layer control devices are additional means of increasing the maximum lift coefficient of a section. The thin layer of air adjacent to the surface of an airfoil shows reduced local velocities from the effect of skin friction. At high angles of attack, the boundary layer on the upper surface tends to stagnate (come to a stop). When this happens, the airflow separates from the surface and stall occurs.

Boundary layer control devices for high-lift applications feature various devices to maintain high velocity in the boundary layer and delay separation of the airflow. Control of the boundary layer's kinetic energy can be accomplished using slats and the application of suction to draw off the stagnant air and replace it with high-velocity air from outside the boundary layer.

Slats (figure 2–32) are movable control surfaces attached to the leading edge of the wing. When the slat is closed, it forms the leading edge of the wing. When in the open position (extended forward), a slot is created between the slat and the wing leading edge. Thus, high-energy air is introduced into the boundary layer over the top of the wing. This is known as "boundary layer control." At low airspeeds this improves handling characteristics, allowing the aircraft to be controlled laterally at airspeeds below the otherwise normal landing speed.

Controlling boundary layer air by surface suction allows the wing to operate at higher angles of attack. The effect on lift characteristics is similar to that of a slot, because the slot is essentially a boundary layer control device ducting high-energy air to the upper surface.

Boundary layer control can also be accomplished by directing high-pressure engine bleed air through a narrow orifice located just forward of the wing

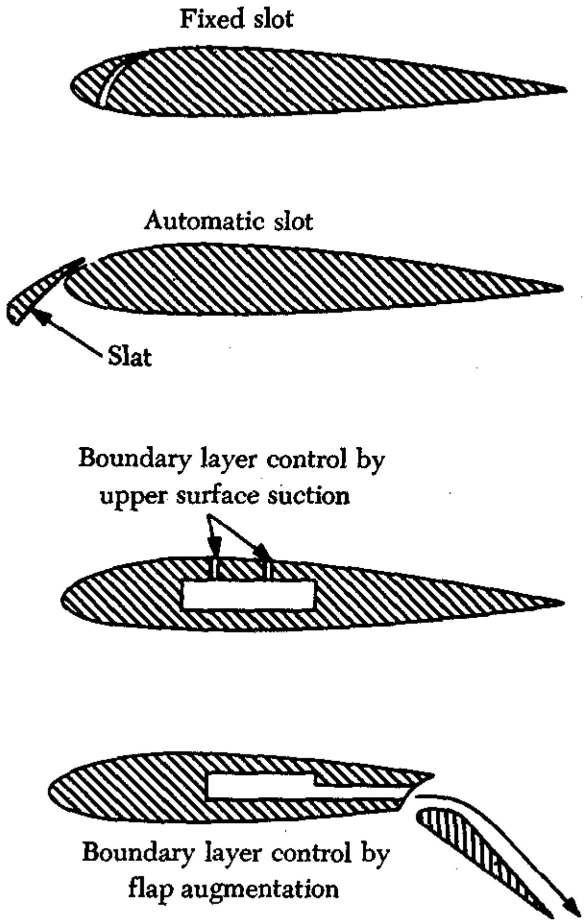


FIGURE 2–32. Methods of controlling boundary layer air.

flap leading edge. This directs a laminar flow (air in layers) of air over the wing and flaps when the flaps have opened sufficiently to expose the orifice. The high-temperature, high-velocity laminar air passing over the wing and flaps delays flow separation (the airstream over an airfoil no longer follows the contour of the airfoil), hence reduces turbulence and drag (see figure 2–29). This results in a lower stall speed and allows slower landing speeds.

FORCES ACTING ON A HELICOPTER

One of the differences between a helicopter and a fixed-wing aircraft is the main source of lift. The fixed-wing aircraft derives its lift from a fixed airfoil surface while the helicopter derives lift from a rotating airfoil called the rotor. Aircraft are classified as either fixed-wing or rotating wing. The word helicopter comes from a Greek word meaning "helical wing" or "rotating wing."

During any kind of horizontal or vertical flight, there are four forces acting on the helicopter—lift, thrust, weight, and drag. Lift is the force required to support the weight of the helicopter. Thrust is the force required to overcome the drag on the fuselage and other helicopter components.

During hovering flight in a no-wind condition, the tip-path plane is horizontal, that is, parallel to the ground. Lift and thrust act straight up; weight and drag act straight down. The sum of the lift and thrust forces must equal the sum of the weight and drag forces in order for the helicopter to hover.

During vertical flight in a no-wind condition, the lift and thrust forces both act vertically upward. Weight and drag both act vertically downward. When lift and thrust equal weight and drag, the helicopter hovers; if lift and thrust are less than weight and drag, the helicopter descends vertically; if lift and thrust are greater than weight and drag, the helicopter rises vertically.

For forward flight, the tip-path plane is tilted forward, thus tilting the total lift-thrust force forward from the vertical. This resultant lift-thrust force can be resolved into two components—lift acting vertically upward, and thrust acting horizontally in the direction of flight. In addition to lift and thrust, there are weight, the downward acting force, and drag, the rearward acting or retarding force of inertia and wind resistance.

In straight-and-level, unaccelerated forward flight, lift equals weight and thrust equals drag. (Straight-and-level flight is flight with a constant heading and at a constant altitude.) If lift exceeds weight, the helicopter climbs; if the lift is less than weight, the helicopter descends. If thrust exceeds drag, the helicopter speeds up; if thrust is less than drag, it slows down.

In sideward flight, the tip-path plane is tilted sideward in the direction that flight is desired thus tilting the total lift-thrust vector sideward. In this case, the vertical or lift component is still straight up, weight straight down, but the horizontal or thrust component now acts sideward with drag acting to the opposite side.

For rearward flight, the tip-path plane is tilted rearward tilting the lift-thrust vector rearward. The thrust component is rearward and drag forward, just the opposite to forward flight. The lift component is straight up and weight straight down.

Torque

Newton's third law of motion states, "To every action there is an equal and opposite reaction." As the main rotor of a helicopter turns in one direction, the fuselage tends to rotate in the opposite direction. This tendency for the fuselage to rotate is called torque. Since torque effect on the fuselage is a direct result of engine power supplied to the main rotor, any change in engine power brings about a corresponding change in torque effect. The greater the engine power, the greater the torque effect. Since there is no engine power being supplied to the main rotor during autorotation, there is no torque reaction during autorotation.

The force that compensates for torque and provides for directional control can be produced by means of an auxiliary rotor located on the end of the tail boom. This auxiliary rotor, generally referred to as a tail rotor, or anti-torque rotor, produces thrust in the direction opposite to torque reaction developed by the main rotor (figure 2–33). Foot pedals in the cockpit permit the pilot to increase or decrease tail-rotor thrust, as needed, to neutralize torque effect.

Other methods of compensating for torque and providing directional control are illustrated in figure 2–33.

The spinning main rotor of a helicopter acts like a gyroscope. As such, it has the properties of gyroscopic action, one of which is precession. Gyroscopic precession is the resultant action or deflection of a spinning object when a force is applied to this object. This action occurs approximately 90° in the direction of rotation from the point where the force is applied (figure 2–34). Through the use of this principle, the tip-path plane of the main rotor may be tilted from the horizontal.

The movement of the cyclic pitch control in a two-bladed rotor system increases the angle of attack of one rotor blade with the result that a greater lifting force is applied at this point in the plane of rotation. This same control movement simultaneously decreases the angle of attack of the other blade a like amount thus decreasing the lifting force applied at this point in the plane of rotation. The blade with the increased angle of attack tends to rise; the blade with the decreased angle of attack tends to lower. However, because of the gyroscopic precession property, the blades do not rise or lower to maximum deflection until a point approximately 90° later in the plane of rotation.

As shown in figure 2–35, the retreating blade angle of attack is increased and the advancing blade angle of attack is decreased resulting in a tipping forward of the tip-path plane, since maxi-

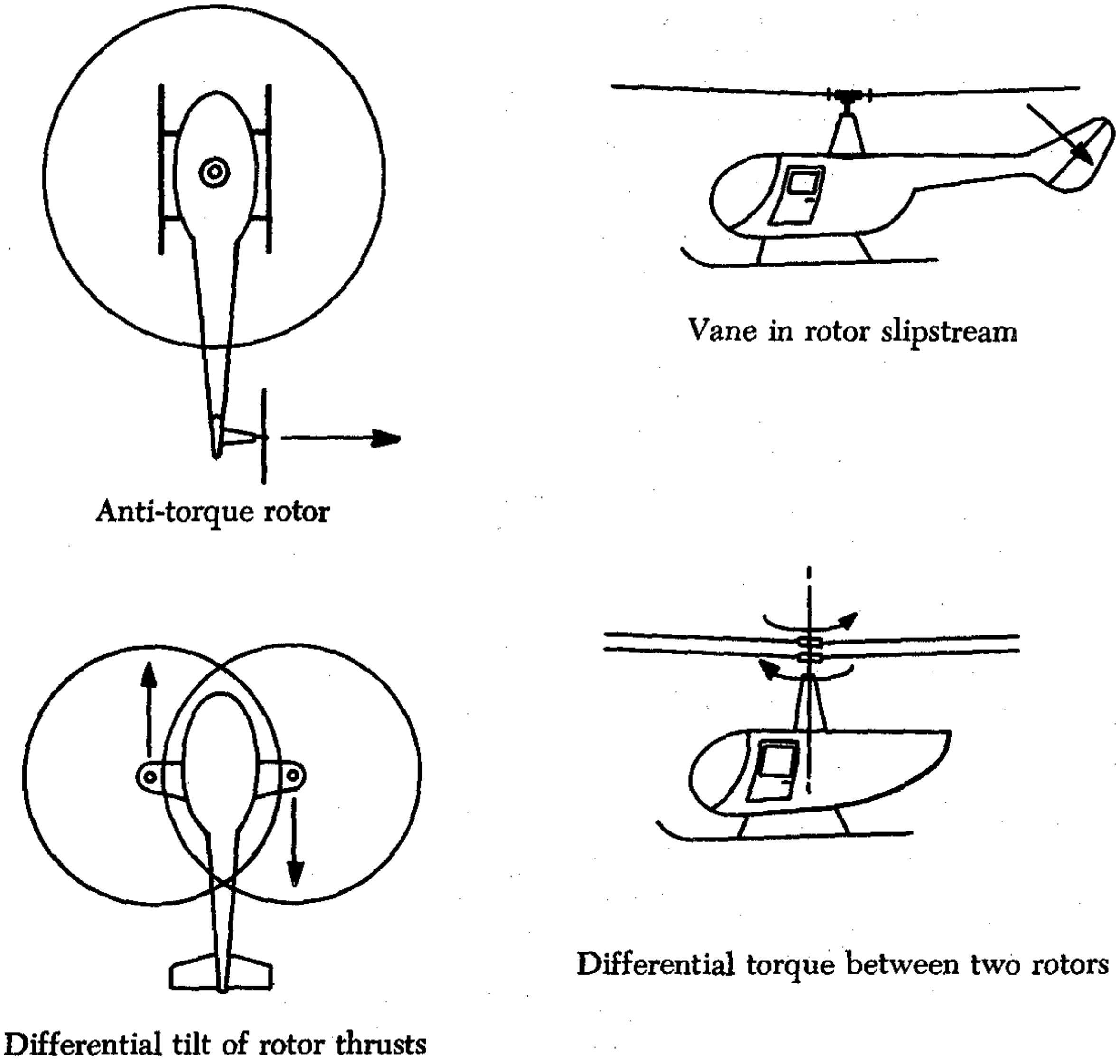


FIGURE 2–33. Methods for achieving directional control.

mum deflection takes place 90° later when the blades are at the rear and front respectively.

In a three-bladed rotor, the movement of the cyclic pitch control changes the angle of attack of each blade an appropriate amount so that the end result is the same, a tipping forward of the tip-path plane when the maximum change in angle of attack is made as each blade passes the same points at which the maximum increase and decrease are made for the two-bladed rotor as shown in figure 2–35. As each blade passes the 90° position on the left, the maximum increase in angle of attack occurs. As each blade passes the 90° position to the right, the maximum decrease in angle of attack occurs. Maximum deflection takes place 90° later, maximum upward deflection at the rear and maximum downward deflection at the front, and the tip-path plane tips forward.

Dissymmetry of Lift

The area within the tip-path plane of the main rotor is known as the disk area or rotor disk. When hovering in still air, lift created by the rotor blades at all corresponding positions around the rotor disk is equal. Dissymmetry of lift is created by horizontal flight or by wind during hovering flight, and is the difference in lift that exists between the advancing blade half of the disk area and the retreating blade half.

At normal rotor operating r.p.m. and zero air-

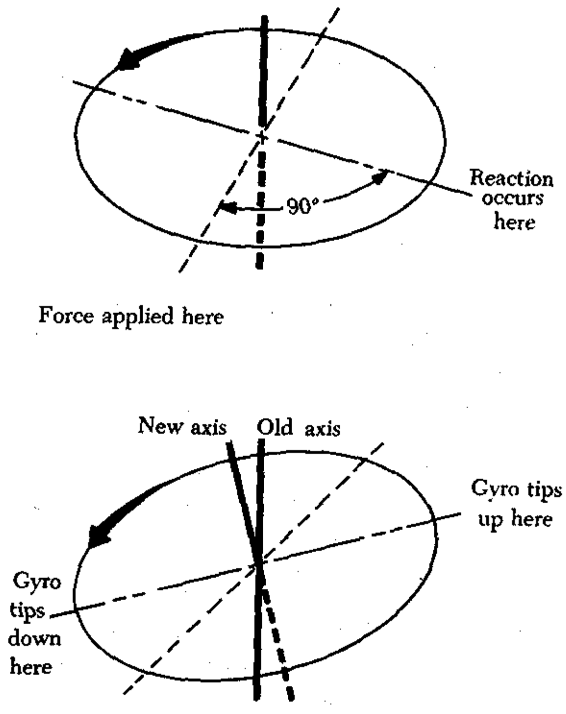


FIGURE 2–34. Gyroscopic precession principle.

speed, the rotating blade tip speed of most helicopter main rotors is approximately 400 m.p.h. When hovering in a no-wind condition, the speed of the relative wind at the blade tips and at any specific point along the blade is the same throughout the tip-path plane (figure 2–36). However, the speed is reduced as this point moves closer to the rotor hub as indicated in figure 2–36 by the two inner circles.

As the helicopter moves into forward flight, the relative wind moving over each rotor blade becomes a combination of the rotational speed of the rotor and the forward movement of the helicopter. As shown in figure 2–37, the advancing blade has the combined speed of the blade velocity plus the speed of the helicopter. On the opposite side, the retreating blade speed is the blade velocity less the speed of the helicopter.

It is apparent that the lift over the advancing blade half of the rotor disk will be greater than the lift over the retreating blade half during horizontal flight or when hovering in a wind.

Due to the greater lift of the advancing blade the helicopter would roll to the left unless something is done to equalize the lift of the blades on both sides of the helicopter.

Blade Flapping

In a three-bladed rotor system, the rotor blades are attached to the rotor hub by a horizontal hinge which permits the blades to move in a vertical plane, *i.e.*, flap up or down, as they rotate (figure 2–38). In forward flight and assuming that the blade-pitch angle remains constant, the increased lift on the advancing blade will cause the blade to flap up decreasing the angle of attack because the relative wind will change from a horizontal direction to more of a downward direction. The decreased lift on the retreating blade will cause the blade to flap down increasing the angle of attack because the relative wind changes from a horizontal direction to more of an upward direction. The com-

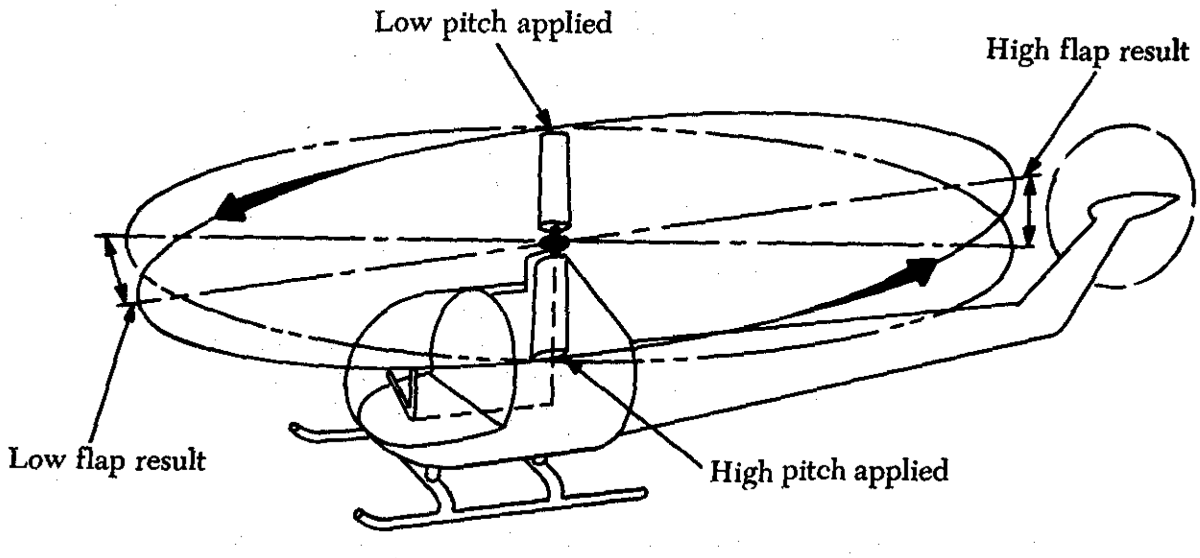


FIGURE 2–35. Rotor disk acts like a gyro.

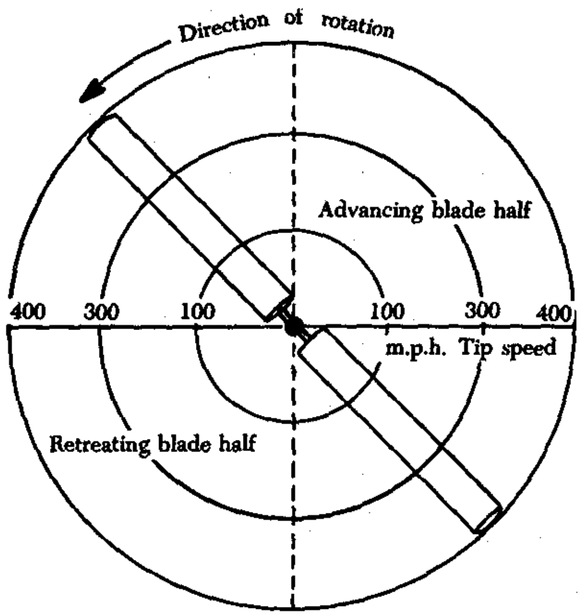


FIGURE 2–36. Comparison of rotor blade speeds for the advancing blade and retreating blade during hover.

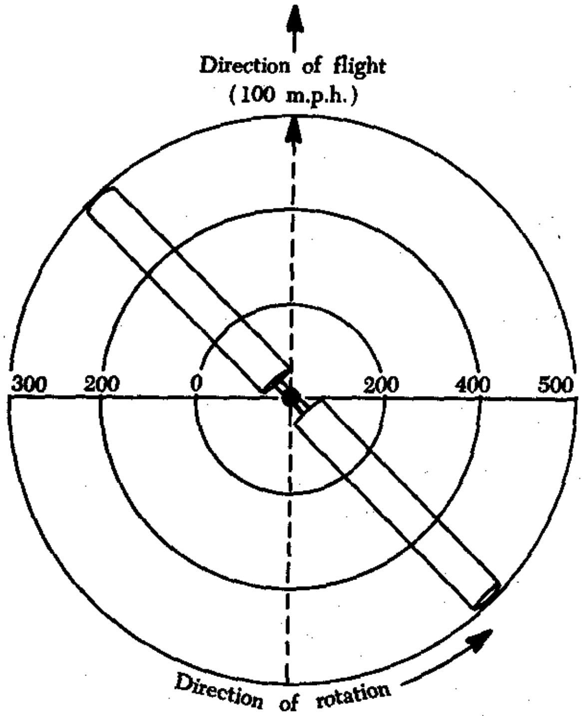


FIGURE 2–37. Comparison of rotor blade speeds for the advancing and retreating blade during forward flight.

bination of decreased angle of attack on the advancing blade and increased angle of attack on the retreating blade through blade flapping action tends

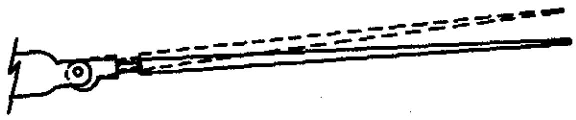


FIGURE 2–38. Blade flapping action (vertical plane).

to equalize the lift over the two halves of the rotor disk.

The amount that a blade flaps up is a compromise between centrifugal force, which tends to hold the blade straight out from the hub, and lift forces which tend to raise the blade on its flapping hinge. As the blades flap up they leave their normal tip-path plane momentarily. As a result, the tip of the blade which is flapping must travel a greater distance. Therefore, it has to travel at a greater speed for a fraction of a second, in order to keep up with the other blades.

The blade flapping action creates an unbalance condition with resulting vibration. To prevent this vibration, a drag hinge (figure 2–39) is incorporated which permits the blade to move back and forth in a horizontal plane.

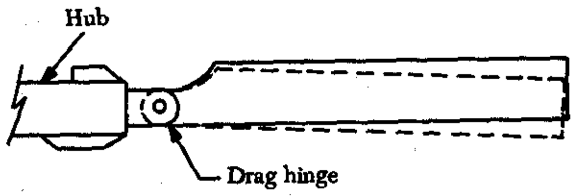


FIGURE 2–39. Action of drag hinge (horizontal plane).

With the blades free to move back and forth on the drag hinges, an unbalanced condition is created since the c.g. (center of gravity) will not remain fixed but moves around the mast. This c.g. movement causes excessive vibration. To dampen out the vibrations, hydraulic dampers limit the movement of the blades on the drag hinge. These dampers also tend to maintain the geometric relationship of the blades.

A main rotor which permits individual movement of the blades from the hub in both a vertical and horizontal plane is called an articulated rotor. The hinge points and direction of motion around each hinge are illustrated in figure 2–40.

In a two-bladed system, the blades flap as a unit. As the advancing blade flaps up due to the increased lift, the retreating blade flaps down due to the decreased lift. The change in angle of attack on

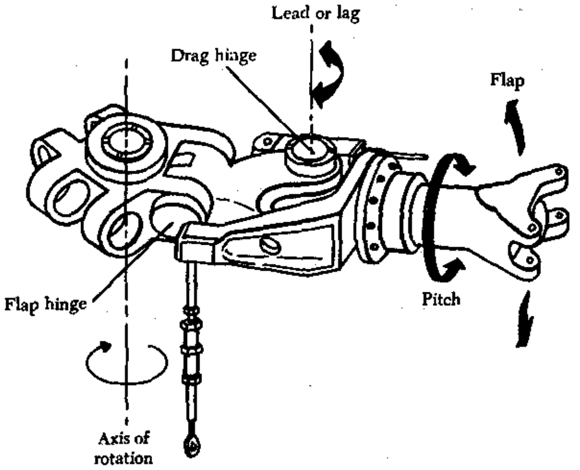


FIGURE 2–40. Articulated rotor head.

each blade brought about by this flapping action tends to equalize the lift over the two halves of the rotor disk.

The position of the cyclic pitch control in forward flight also causes a decrease in angle of attack on the advancing blade and an increase in angle of attack on the retreating blade. This together with blade flapping equalizes lift over the two halves of the rotor disk.

Coning

Coning (figure 2–41) is the upward bending of the blades caused by the combined forces of lift and centrifugal force. Before takeoff, the blades rotate in a plane nearly perpendicular to the rotor mast, since centrifugal force is the major force acting on them.

As a vertical takeoff is made, two major forces are acting at the same time—centrifugal force acting outward perpendicular to the rotor mast, and lift acting upward and parallel to the mast. The result of these two forces is that the blades assume

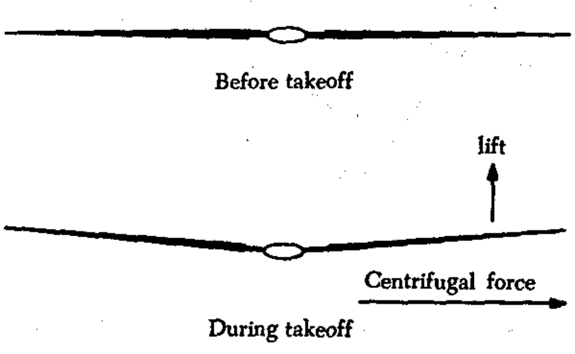


FIGURE 2–41. Blade coning.

a conical path instead of remaining in the plane perpendicular to the mast.

Coning results in blade bending in a semirigid rotor; in an articulated rotor, the blades assume an upward angle through movement about the flapping hinges.

Ground Effect

When a helicopter is in a hovering position close to the ground, the rotor blades will be displacing air downward through the disk faster than it can escape from beneath the helicopter. This builds up a cushion of dense air between the ground and the helicopter (figure 2–42). This cushion of more dense air, referred to as ground effect, aids in supporting the helicopter while hovering. It is usually effective to a height of approximately one-half the rotor disk diameter. At approximately 3 to 5 m.p.h. groundspeed, the helicopter will leave its ground cushion.

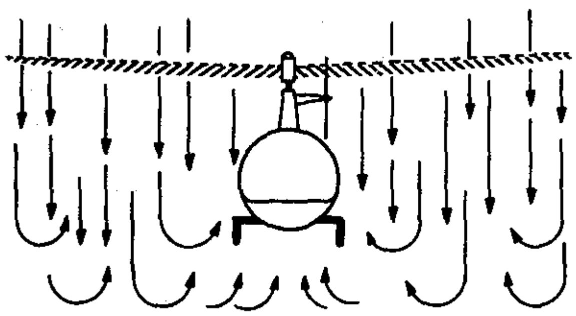


FIGURE 2–42. Ground effect.

Autorotation

Autorotation is the term used for the flight condition during which no engine power is supplied and the main rotor is driven only by the action of the relative wind. The helicopter transmission or power train is designed so that the engine, when it stops, is automatically disengaged from the main rotor system to allow the main rotor to rotate freely in its original direction.

When engine power is being supplied to the main rotor, the flow of air is downward through the rotor. When engine power is not being supplied to the main rotor, that is, when the helicopter is in autorotation, the flow of air is upward through the rotor. It is this upward flow of air that causes the rotor to continue turning after engine failure.

The portion of the rotor blade that produces the forces that cause the rotor to turn when the engine is no longer supplying power to the rotor, is that portion between approximately 25% and 70% of the radius outward from the center. This portion is often referred to as the "autorotative or driving region." Aerodynamic forces along this portion of the blade tend to speed up the blade rotation.

The inner 25% of the rotor blade, referred to as the "stall region," operates above its maximum angle of attack (stall angle), thereby contributing little lift but considerable drag which tends to slow the blade rotation.

The outer 30% of the rotor blade is known as the "propeller or driven region." Aerodynamic forces here result in a small drag force which tends to slow the tip portion of the blade.

The aerodynamic regions as described above are for vertical autorotations. During forward flight autorotations, these regions are displaced across the rotor disk to the left.

Rotor r.p.m. stabilizes when the autorotative forces (thrust) of the "driving region" and the autorotative forces (drag) of the "driven region" and the "stall region" are equal.

Forward speed during autorotative descent permits a pilot to incline the rotor disk rearward, thus causing a flare. The additional induced lift created by the greater volume of air momentarily checks forward speed as well as descent. The greater volume of air acting on the rotor disk will normally increase rotor r.p.m. during the flare. As the forward speed and descent rate near zero, the upward flow of air has practically ceased and rotor r.p.m. again decreases; the helicopter settles at a slightly increased rate but with reduced forward speed. The flare enables the pilot to make an emergency landing on a definite spot with little or no landing roll or skid.

HELICOPTER AXES OF FLIGHT

As a helicopter maneuvers through the air, its attitude in relation to the ground changes. These changes are described with reference to three axes (figure 2–43) of flight: (1) Vertical, (2) longitudinal, and (3) lateral.

Movement about the vertical axis produces yaw, a nose swing (or change in direction) to the right or left. This is controlled by the directional-control pedals. The various methods of achieving directional control were discussed earlier in this section.

Movement about the longitudinal axis is called roll. This movement is effected by moving the cyclic pitch control to the right or left. The cyclic pitch control is similar to the control stick of a conventional aircraft. It acts through a mechanical linkage (figure 2–44) to change the pitch of each main-rotor blade during a cycle of rotation.

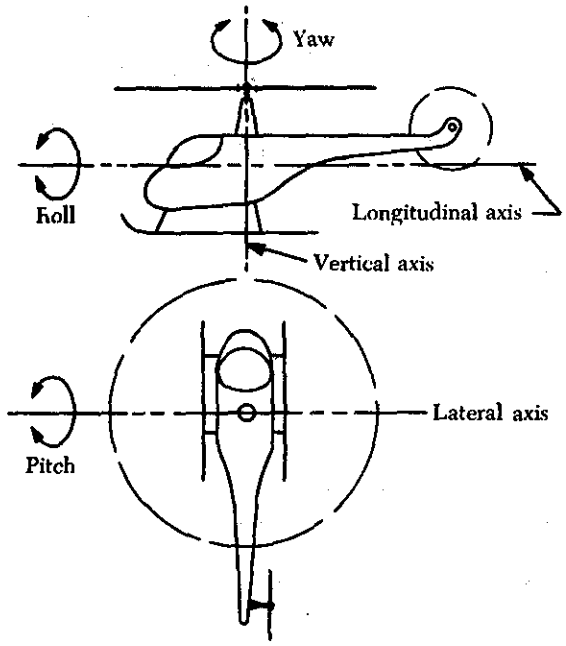


FIGURE 2–43. Axes of flight.

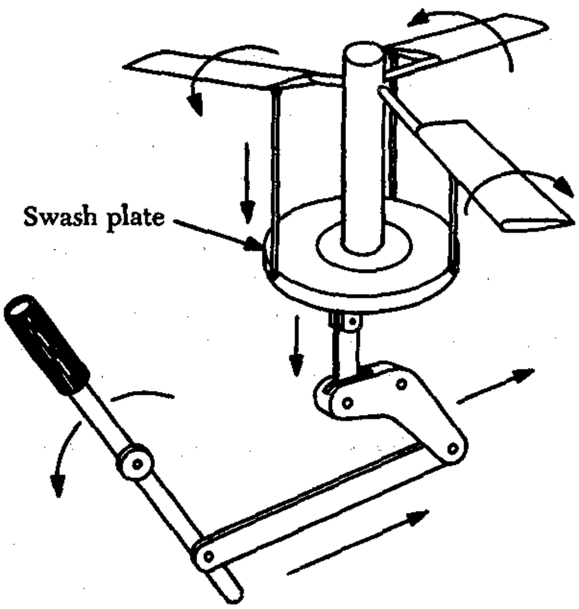


FIGURE 2–44. Cyclic pitch control mechanism.

The rapidly rotating rotor blades create a disk area that can be tilted in any direction with respect to the supporting rotor mast. Horizontal movement is controlled by changing the direction of tilt of the main rotor to produce a force in the desired direction.

Movement about the lateral axis produces a noseup or nosedown attitude. This movement is effected by moving the cyclic pitch control fore and aft.

The collective pitch control (figure 2-45) varies the lift of the main rotor by increasing or decreasing the pitch of all blades at the same time. Raising the collective pitch control increases the pitch of the blades, thereby increasing the lift. Lowering the control decreases the pitch of the blades, causing a loss of lift. Collective pitch control is also used in coordination with cyclic pitch control to regulate the airspeed of the helicopter.

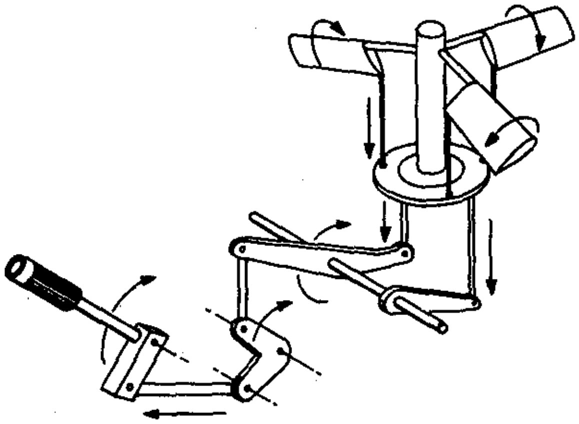


FIGURE 2-45. Collective pitch control mechanism.

Many factors determine the amount of lift available in helicopter operation. Generally speaking, the pilot has control of two of these. One is the pitch angle of the rotor blades; the other is the power delivered to the rotor, represented by r.p.m. and manifold pressure. By controlling the pitch angle of the rotor blades, the pilot can establish the vertical flight of the helicopter. By manipulating the throttle control, a constant engine speed can be maintained regardless of the increase or decrease in blade pitch. The throttle is mounted on the collective pitch grip and is operated by rotating the grip. The throttle is synchronized with the main-rotor pitch control in such a manner that an increase of pitch increases power and a decrease in pitch decreases power. A complete control system of a conventional helicopter is shown in figure 2-46.

HIGH-SPEED AERODYNAMICS

Developments in aircraft and powerplants are yielding high-performance transports with capabilities for very high speed flight. Many significant differences arise in the study of high-speed aerodynamics when compared with low-speed aerodynamics. It is quite necessary, therefore, that persons associated with commercial aviation be familiar with the nature of high-speed airflow and the peculiarities of high-performance airplanes.

General Concepts of Supersonic Flow Patterns

At low flight speeds, air experiences small changes in pressure which cause negligible variations in density, greatly simplifying the study of low-speed aerodynamics. The flow is called incompressible since the air undergoes small changes in pressure without significant changes in density. At high flight speeds, however, the pressure changes that take place are quite large and significant changes in air density occur. The study of airflow at high speeds must account for these changes in air density and must consider that the air is compressible, or that there are compressibility effects.

The speed of sound is very important in the study of high-speed airflow. The speed of sound varies with the ambient temperature. At sea level, on a standard day, the speed of sound is about 661.7 knots (760 m.p.h.).

As a wing moves through the air, local velocity changes occur which create pressure disturbances in the airflow around the wing. These pressure disturbances are transmitted through the air at the speed of sound. If the wing is traveling at low speed, the pressure disturbances are transmitted and extend indefinitely in all directions. Evidence of these pressure disturbances is seen in the typical subsonic flow pattern illustrated in figure 2-47 where upwash and flow direction change well ahead of the wing leading edge.

If the wing is traveling above the speed of sound, the airflow ahead of the wing is not influenced by the pressure field of the wing, since pressure disturbances cannot be propagated faster than the speed of sound. As the flight speed nears the speed of sound, a compression wave forms at the leading edge and all changes in velocity and pressure take place quite sharply and suddenly. The airflow ahead of the wing is not influenced until the air molecules are suddenly forced out of the way by the wing. Evidence of this phenomenon is seen in the typical supersonic flow pattern shown in figure 2-48.

Compressibility effects depend not on airspeed, but rather on the relationship of airspeed to the

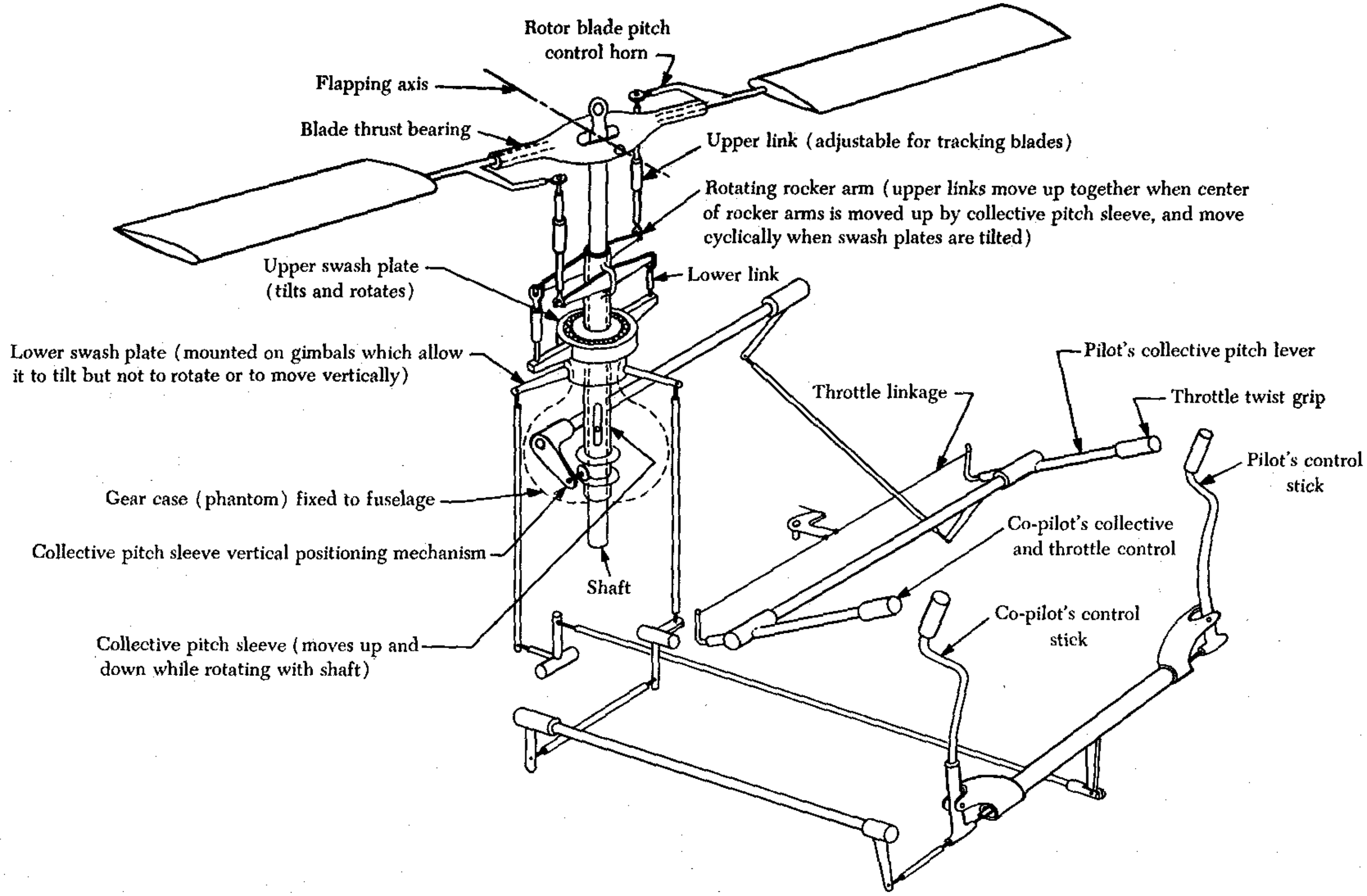


FIGURE 2–46. Control system of conventional helicopter.

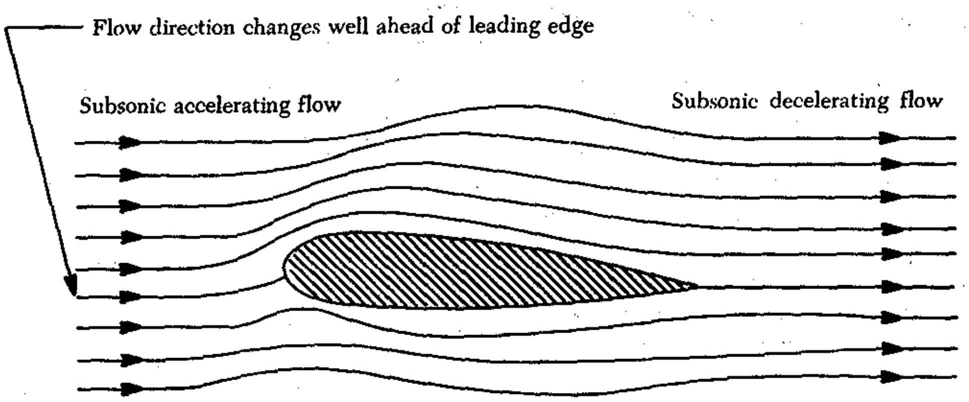


FIGURE 2–47. Typical subsonic flow pattern, subsonic wing.

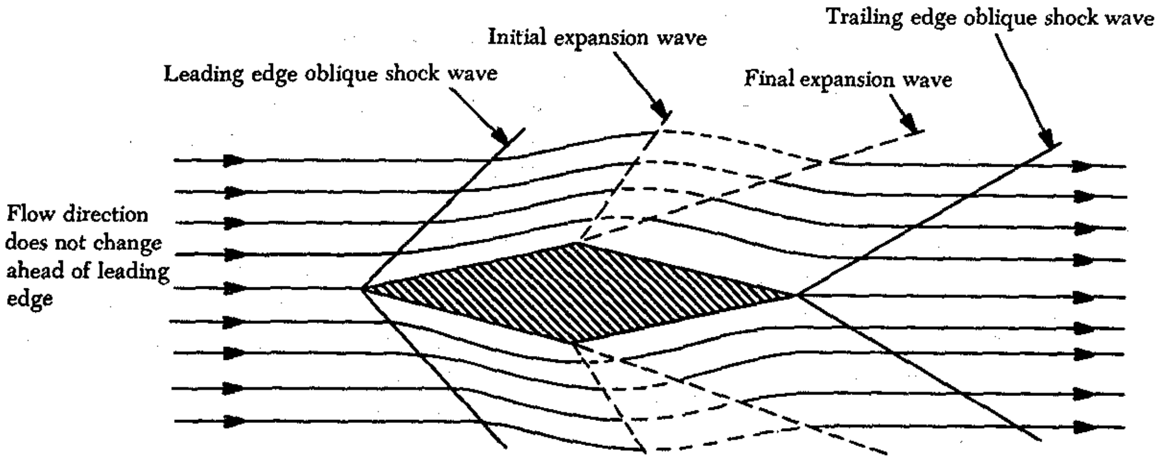


FIGURE 2–48. Typical supersonic flow pattern, supersonic wing.

speed of sound. This relationship is called Mach number, and is the ratio of true airspeed to the speed of sound at a particular altitude.

Compressibility effects are not limited to flight speeds at and above the speed of sound. Since any airplane is made up of aerodynamic shapes, air accelerates and decelerates around these shapes and attains local speeds above the flight speed. Thus, an aircraft can experience compressibility effects at flight speeds well below the speed of sound. Since it is possible to have both subsonic and supersonic flows on the airplane at the same time, it is best to define certain regimes of flight. These approximate regimes are defined as follows:

(1) Subsonic—flight Mach numbers below 0.75.

(2) Transonic—flight Mach numbers from 0.75 to 1.20.

(3) Supersonic—flight Mach numbers from 1.20 to 5.00.

(4) Hypersonic—flight Mach numbers above 5.00.

While the flight Mach numbers used to define these regimes are approximate, it is important to appreciate the types of flow existing in each area. In the subsonic regime, subsonic airflow exists on all parts of the aircraft. In the transonic regime, the flow over the aircraft components is partly subsonic and partly supersonic. In the supersonic and hypersonic regimes, supersonic flow exists over all parts of the aircraft. Of course, in supersonic and hypersonic flight some portions of the boundary layer are subsonic, but the predominating flow is still supersonic.

Difference Between Subsonic and Supersonic Flow

In a subsonic flow every molecule is affected more or less by the motion of every other molecule in the whole field of flow. At supersonic speeds, an air molecule can influence only that part of the flow contained in the Mach cone formed behind that molecule.

The peculiar differences between subsonic flow and supersonic flow can best be seen by considering airflow in a closed contracting/expanding tube, as depicted in figure 2-48.

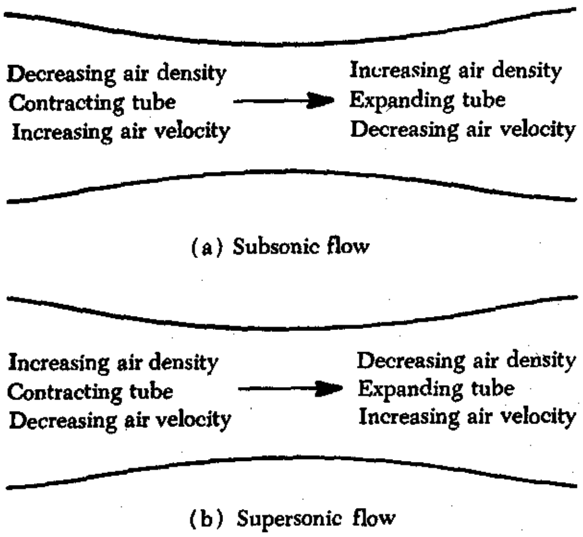


FIGURE 2-49. Comparison of subsonic and supersonic airflow through a closed tube.

Unlike subsonic flow, a supersonic airstream accelerates along an expanding tube, causing the air density to decrease rapidly to compensate for the combined effects of increased speed and increased cross sectional area.

Unlike subsonic flow, a supersonic airstream decelerates along a contracting tube, causing the air density to increase rapidly to compensate for the combined effects of decreased speed and decreased cross sectional area.

In order to clarify these fundamental points, figure 2-50 lists the nature of the two types of tubes. An understanding of figures 2-49 and 2-50 is essential if one is to grasp the fundamentals of supersonic flow.

	Contracting tube	*Expanding tube*
Subsonic flow	Accelerates and rarefies slightly	Decelerates and compresses slightly
Supersonic flow	Decelerates and compresses greatly	Accelerates and rarefies greatly

FIGURE 2-50. High-speed flows.

TYPICAL SUPERSONIC FLOW PATTERNS

With supersonic flow, all changes in velocity, pressure, temperature, density, and flow direction take place suddenly and over a short distance. The areas of flow change are distinct and the phenomena causing the flow change are called wave formations. All compression waves occur abruptly and are wasteful of energy. Compression waves are more familiarly known as shock waves. Expansion waves result in smoother flow transition and are not wasteful of energy like shock waves. Three types of waves can take place in supersonic flow: (1) The oblique (inclined angle) shock wave (compression), (2) the normal (right angle) shock wave (compression), and (3) the expansion wave (no shock). The nature of the wave depends on the Mach number, the shape of the object causing the flow change, and the direction of flow.

A supersonic airstream passing through the oblique shock wave experiences these changes:

(1) The airstream is slowed down. Both the velocity and the Mach number behind the wave are reduced, but the flow is still supersonic.
(2) The flow direction is changed so that the airstream runs parallel to the new surface.
(3) The static pressure behind the wave is increased.
(4) The static temperature behind the wave is increased (and hence the local speed of sound is increased).
(5) The density of the airstream behind the wave is increased.
(6) Some of the available energy of the airstream (indicated by the sum of dynamic and static pressure) is dissipated by conversion into unavailable heat energy. Hence, the shock wave is wasteful of energy.

The Normal Shock Wave

If a blunt-nosed object is placed in a supersonic airstream, the shock wave which is formed is detached from the leading edge. The detached wave

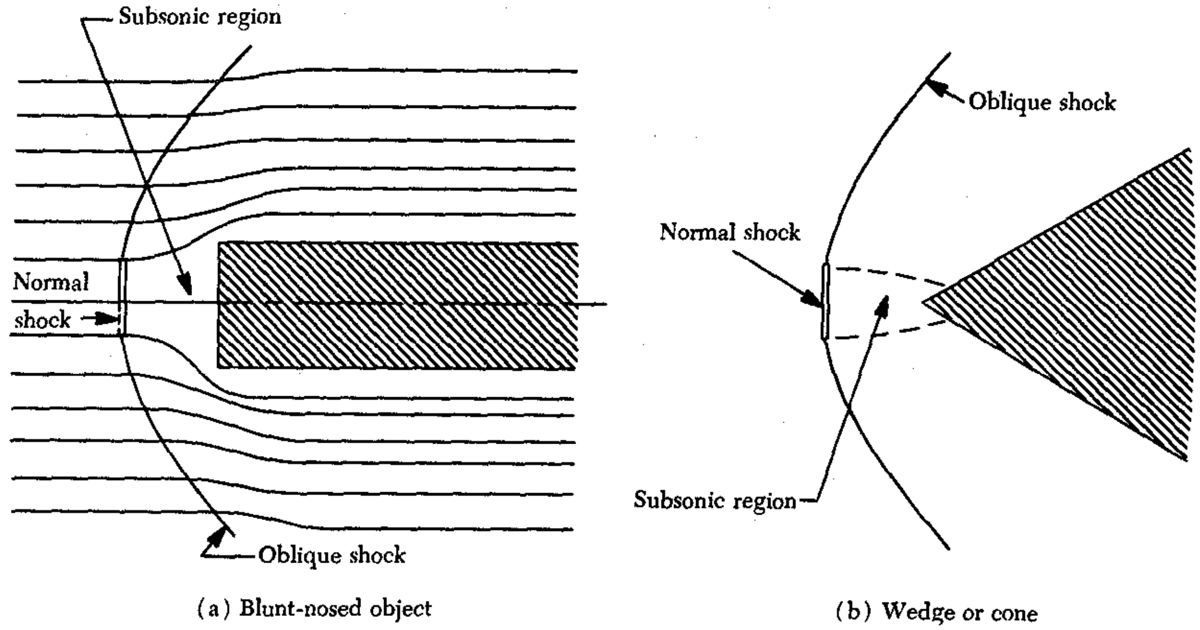


FIGURE 2–51. Normal shock-wave formation with a detached wave.

also occurs when a wedge or cone half angle exceeds some critical value. Figure 2–51 shows the formation of a normal shock wave in the above two cases. Whenever a shock wave forms perpendicular to the free stream flow, the shock wave is termed a normal (right angle) shock wave and the flow immediately behind the wave is subsonic. No matter how high the free stream Mach number may be, the flow directly behind a normal shock is always subsonic. In fact, the higher the supersonic free stream Mach number (M) is in front of the normal shock wave, the lower the subsonic Mach number is aft of the wave. For example, if M_1 is 1.5, M_2 is 0.7; while if M_1 is 2.6, M_2 is only 0.5. A normal shock wave forms immediately in front of any relatively blunt object in a supersonic airstream, slowing the airstream to subsonic so that the airstream may feel the presence of the blunt object and thus flow around it. Once past the blunt nose, the airstream may remain subsonic or it may accelerate back to supersonic, depending on the shape of the nose and the Mach number of the free stream.

A normal wave may also be formed when there is no object in the supersonic airstream. It so happens that whenever a supersonic airstream is slowed to subsonic without a change in direction, a normal shock wave forms as the boundary between the supersonic and subsonic regions. This is why airplanes encounter compressibility effects before the flight speed is sonic. Figure 2–52 illustrates the manner in which an airfoil at a high subsonic speed has local flow velocities which are supersonic. As the local supersonic flow moves aft, a normal shock wave forms so that the flow may return to subsonic and rejoin the subsonic free stream at the trailing edge without discontinuity. The transition of flow from subsonic to supersonic is smooth and is not accompanied by shock waves if the transition is made gradually with a smooth surface. The transition of flow from supersonic to subsonic without direction change always forms a normal shock wave.

A supersonic airstream passing through a normal shock wave experiences these changes:

(1) The airstream is slowed to subsonic. The local Mach number behind the wave is approximately equal to the reciprocal of the Mach number ahead of the wave. For example, if the Mach number ahead of the wave is 1.25, the Mach number of the flow behind the wave is about 0.8 (more exactly 0.81264).

(2) The airflow direction immediately behind the wave is unchanged.

(3) The static pressure behind the wave is greatly increased.

(4) The static temperature behind the wave is

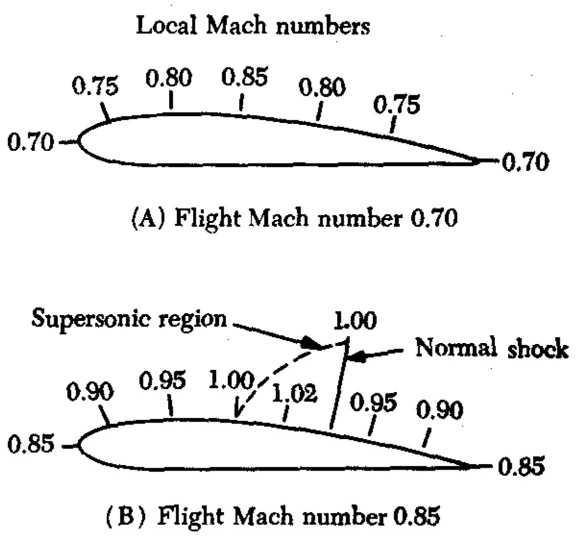


FIGURE 2–52. Normal shock-wave formation on an airfoil in a subsonic airstream.

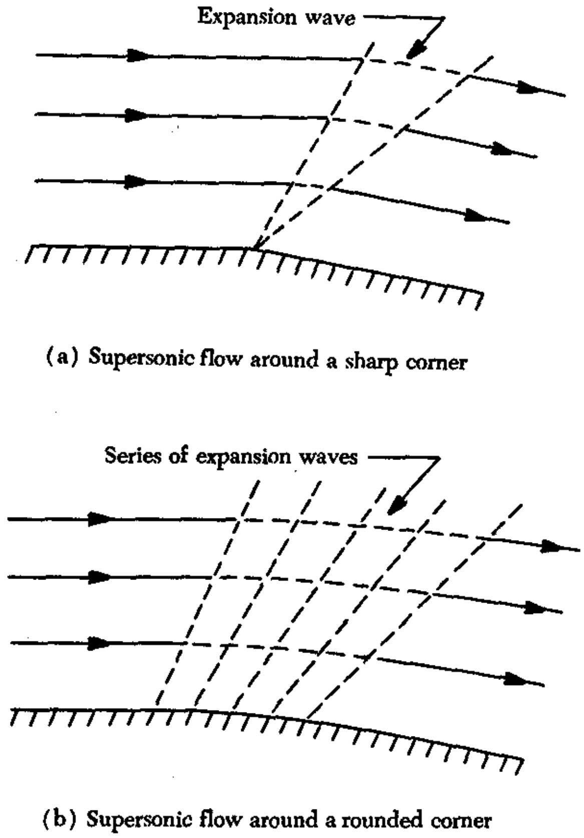


FIGURE 2–53. Expansion wave formation.

greatly increased (and hence the local speed of sound is increased).

(5) The density of the airstream behind the wave is greatly increased.

(6) The available energy of the airstream (indicated by the sum of dynamic and static pressure) is greatly reduced. The normal shock wave is very wasteful of energy.

The Expansion Wave

If a supersonic airstream is turned away from the preceding flow, an expansion wave is formed. The flow around a corner shown in figure 2–53 does not cause sharp, sudden changes in the airflow except at the corner itself and thus is not actually a shock wave. A supersonic airstream passing through an expansion wave experiences these changes:

(1) The supersonic airstream is accelerated. The velocity and Mach number behind the wave are greater.

(2) The flow direction is changed so that the airstream runs parallel to the new surface, provided separation does not occur.

(3) The static pressure behind the wave is decreased.

(4) The static temperature behind the wave is decreased (and hence the local speed of sound is decreased).

(5) The density of the airstream behind the wave is decreased.

(6) Since the flow changes in a rather gradual manner, there is no shock and no loss of energy in the airstream. The expansion wave does not dissipate airstream energy.

A summary of the characteristics of the three principal wave forms encountered with supersonic flow is shown in figure 2–54.

Figure 2–55 shows the wave pattern for a conventional blunt-nosed subsonic airfoil in a supersonic stream. When the nose is blunt, the wave must detach and become a normal shock wave immediately ahead of the leading edge. Since the flow just behind a normal shock wave is always subsonic, the airfoil's leading edge is in a subsonic region of very high static pressure, static temperature, and density.

In supersonic flight, the zero lift of an airfoil of some finite thickness includes a wave drag. Wave drag is separate and distinct from drag due to lift. The thickness of the airfoil has an extremely powerful effect on the wave drag. The wave drag varies as the square of the thickness ratio (maximum thickness divided by the chord). For example, if the thickness is cut by one-half, the wave drag is cut by three-fourths. The leading edges of supersonic

Type of wave	Flow direction change	Effect on velocity and Mach number	Effect on static pressure, static temperature and density	Effect on available energy
 Oblique shock wave	Flow into a corner	Decreased, but still supersonic	Increase	Decrease
 Normal shock wave	No change	Decreased to subsonic	Great increase	Great decrease
 Expansion wave	Flow around a corner	Increased to higher supersonic	Decrease	No change (no shock)

FIGURE 2–54. Supersonic wave characteristics.

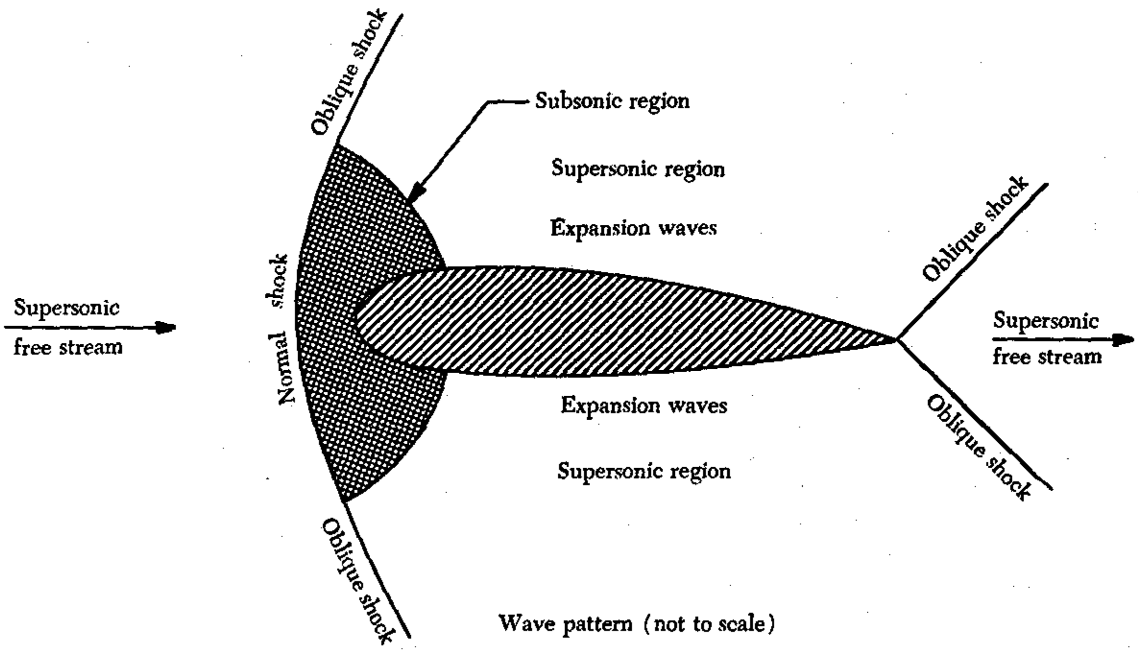


FIGURE 2–55. The conventional subsonic airfoil in supersonic flow.

shapes must be sharp. If they are not, the wave formed near the leading edge is a strong detached normal shock wave.

Once the flow over the airfoil is supersonic, the aerodynamic center of the surface is located approximately at the 50% chord position. This contrasts with the subsonic location of the aerodynamic center, which is near the 25% chord position.

During supersonic flow all changes in velocity, Mach number, static pressure, static temperature, density, and flow direction take place quite suddenly through the various wave forms. The shape of the object, the Mach number, and the required flow direction change dictate the type and strength of the wave formed.

Any object in subsonic flight which has some finite thickness or is producing lift must have local velocities on the surface which are greater than the free stream velocity. Hence, compressibility effects can be expected to occur at flight speeds which are less than the speed of sound. The transonic regime of flight provides the opportunity for mixed subsonic and supersonic local velocities and accounts for the first significant effects of compressibility.

As the flight speed approaches the speed of sound, the areas of supersonic flow enlarge and the shock waves move nearer the trailing edge. The boundary layer may remain separated or may re-attach, depending much upon the airfoil shape and angle of attack. When the flight speed exceeds the speed of sound, a bow wave suddenly appears in front of the leading edge with a subsonic region behind the wave. The normal shock waves move to the trailing edge. If the flight speed is increased to some higher supersonic value, the bow wave moves closer to the leading edge and inclines more downstream, and the trailing edge normal shock waves become oblique shock waves.

Of course, all components of the aircraft are affected by compressibility in a manner somewhat similar to that of the basic airfoil (the empennage, fuselage, nacelles, and so forth).

Since most of the difficulties of transonic flight are associated with shock-wave-induced flow separation, any means of delaying or lessening the shock-induced separation improves the aerodynamic characteristics. An aircraft configuration can make use of thin surfaces of low aspect ratio with sweepback to delay and reduce the magnitude of transonic force divergence. In addition, various methods of boundary layer control, high-lift devices, vortex generators, and so forth, may be applied to improve transonic characteristics. For example, the mounting of vortex generators on a surface can produce higher local surface velocities and increase the kinetic energy of the boundary layer. Thus, a more severe pressure gradient (stronger shock wave) would be necessary to produce the unwanted airflow separation.

A vortex generator is a complementary pair of small, low aspect ratio (short span in relation to chord) airfoils mounted at opposite angles of attack to each other and perpendicular to the aerodynamic surface they serve. Figure 2–56 shows the airfoils and the airflow characteristics of a vortex generator. Like any airfoil, those of the generator develop lift. In addition, like any airfoil of especially low aspect ratio, the airfoils of the generator also develop very strong tip vortices. These tip vortices cause air to flow outward and inward in circular paths around the ends of the airfoils. The vortices generated have the effect of drawing high-energy air from outside the boundary layer into the slower moving air close to the skin. The strength of the vortices is proportional to the lift developed by the airfoils of the generator.

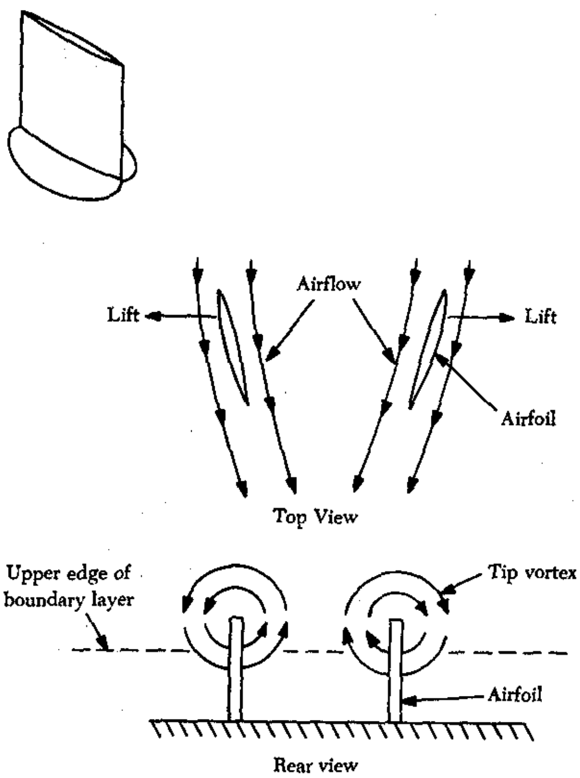


FIGURE 2–56. Wing vortex generator.

Vortex generators serve two distinctly different purposes, depending on the aerodynamic surface upon which they are mounted. Rows of vortex generators located on the upper surface of the wing just upstream of the ailerons delay the onset of drag divergence at high speeds and also aid in maintaining aileron effectiveness at high speeds. In contrast, rows of vortex generators mounted on both sides of the vertical fin just upstream of the rudder prevent flow separation over the rudder during extreme angles of yaw which are attained only when rudder application is delayed after an engine loss at very low speeds. In addition, rows of vortex generators placed on the underside (and occasionally on the upper surface) of the horizontal stabilizer just upstream of the elevators prevent flow separation over the elevators at very low speeds.

In summary, vortex generators on wing surfaces improve high-speed characteristics, while vortex generators on tail surfaces, in general, improve low-speed characteristics.

Control Surfaces

The control surfaces used on aircraft operating at transonic and supersonic flight speeds involves some important considerations. Trailing edge control surfaces can be affected adversely by the shock waves formed in flight above the control surface critical Mach number. If the airflow is separated by the shock wave, the resulting buffet of the control surface can be very objectionable. Installation of vortex generators can reduce buffet caused by shock-induced flow separation. In addition to the buffet of the surface, the change in the pressure distribution due to separation and shock-wave location can create very large changes in control surface hinge moments. Such large changes in hinge moments produce undesirable control forces which may require the use of an irreversible control system. An irreversible control system employs powerful hydraulic or electric actuators to move the control surfaces, hence the airloads developed on the surfaces cannot be felt by the pilot. Suitable feedback must be synthesized by bungees, "q" springs, bobweights, and so forth.

AERODYNAMIC HEATING

When air flows over any aerodynamic surface, certain reductions in velocity take place which produce corresponding increases in temperature. The greatest reduction in velocity and increase in temperature occur at the various stagnation points on the aircraft. Of course, smaller changes occur at other points on the aircraft, but these lower temperatures can be related to the ram temperature rise at the stagnation point. While subsonic flight does not produce temperatures of any real concern, supersonic flight can create temperatures high enough to be of major importance to the airframe, fuel system, and powerplant.

Higher temperatures produce definite reductions in the strength of aluminum alloys and require the use of titanium alloys and stainless steels. Continued exposure at elevated temperatures further reduces strength and magnifies the problems of creep failure and structural stiffness.

The effect of aerodynamic heating on the fuel system must be considered in the design of a supersonic airplane. If the fuel temperature is raised to the spontaneous ignition temperature, the fuel vapors will burn in the presence of air without the need of an initial spark or flame.

Turbojet engine performance is adversely affected by high compressor inlet air temperature. The thrust output of the turbojet, obviously, is some function of the fuel flow. But the maximum allowable fuel flow depends on the maximum permissible turbine operating temperature. If the air entering the engine is already hot, less fuel can be added in order to avoid exceeding turbine temperature limits.

FLIGHT CONTROL SYSTEMS

Three types of control systems commonly used are: (1) The cable, (2) push-pull, and (3) the torque tube system. The cable system is the most widely used because deflections of the structure to which it is attached do not affect its operation. Many aircraft incorporate control systems that are combinations of all three types.

Flight Control System Hardware, Mechanical Linkage, and Mechanisms

The systems which operate the control surfaces, tabs, and flaps include flight control system hardware, linkage, and mechanisms. These items connect the control surfaces to the cockpit controls. Included in these systems are cable assemblies, cable guides, linkage, adjustable stops, control surface snubber or locking devices, surface control booster units, actuators operated by electric motors, and actuators operated by hydraulic motors.

Cable Assembly

The conventional cable assembly consists of flexible cable, terminals (end fittings) for attaching to other units, and turnbuckles. Information concerning conventional cable construction and end fittings is contained in Chapter 6 of the Airframe and Powerplant Mechanics General Handbook, AC 65–9A.

At each regular inspection period, cables should be inspected for broken wires by passing a cloth along their length and observing points where the cloth snags. To thoroughly inspect the cable, move the surface control to its extreme travel limits. This will reveal the cable in pulley, fairlead, and drum areas. If the surface of the cable is corroded, relieve cable tension. Then carefully force the cable open by reverse twisting, and visually inspect the interior for corrosion. Corrosion on the interior strands of the cable indicates failure of the cable and requires replacement of the cable. If there is no internal corrosion, remove external corrosion with a coarse-weave rag or fiber brush. Never use metallic wools or solvents to clean flexible cable. Metallic wools imbed dissimilar metal particles, which cause further corrosion. Solvents remove the internal cable lubricant, which also results in further corrosion. After thoroughly cleaning the flexible cable, apply corrosion-preventive compound. This compound preserves and lubricates the cable.

Breakage of wires occurs most frequently where cables pass over pulleys and through fairleads. Typical breakage points are shown in figure 2–57. Control cables and wires should be replaced if worn, distorted, corroded, or otherwise damaged.

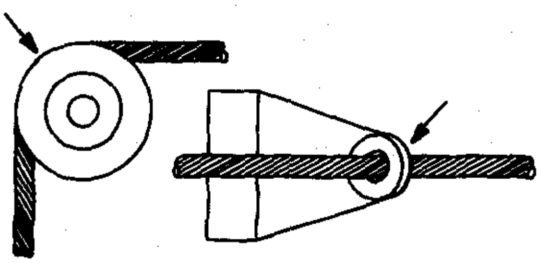


FIGURE 2–57. Typical breakage points.

Lockclad cable is used on some large aircraft for all long, straight runs. It consists of the conventional flexible steel cable with aluminum tubing swaged to it to lock the cable inside the tubing. Lockclad cable construction has certain advantages. Changes in tension due to temperature are less than with conventional cable. Furthermore, the amount of stretch at a given load is less than with conventional cable.

Lockclad cables should be replaced when the covering is worn through, exposing worn wire strands; is broken; or shows worn spots which cause the cable to bump when passing over fairlead rollers.

Turnbuckles

The turnbuckle is a device used in cable control systems to adjust cable tension. The turnbuckle barrel is threaded with left-hand threads inside one end and right-hand threads inside the other. When adjusting cable tension, the cable terminals are screwed into either end of the barrel an equal distance by turning the barrel. After a turnbuckle is adjusted, it must be safetied. The methods of safetying turnbuckles is discussed in Chapter 6 of the Airframe and Powerplant Mechanics General Handbook, AC 65–9.

Cable Connectors

In addition to turnbuckles, cable connectors are used in some systems. These connectors enable a cable length to be quickly connected or disconnected from a system. Figure 2–58 illustrates one type of cable connector in use. This type is connected or disconnected by compressing the spring.

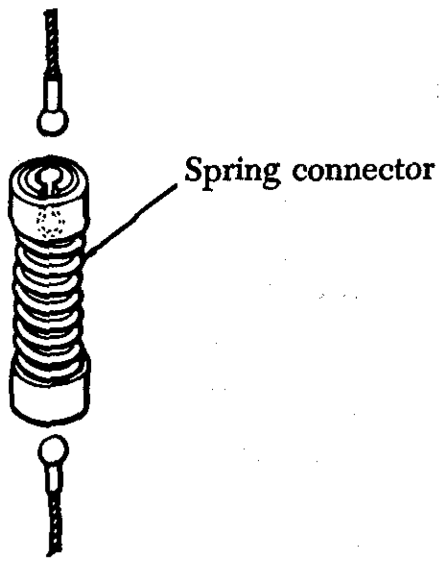


FIGURE 2–58. Spring type of cable connector.

HYDRAULIC OPERATED CONTROL SYSTEMS

As the airspeed of late model aircraft increased, actuation of controls in flight became more difficult. It soon became apparent that the pilot needed assistance to overcome the airflow resistance to control movement. Spring tabs which were operated by the conventional control system were moved so that the airflow over them actually moved the primary control surface. This was sufficient for the aircraft operating in the lowest of the high speed ranges (250–300 mph).

For high speeds a power assist (hydraulic) control system was designed.

Conventional cable or push pull rod systems are installed and are tied into a power transmission quadrant. With the system activated, the pilot's effort is used to open valves thereby directing hydraulic fluid to actuators, which are connected to the control surfaces by control rods. The actuators move the control surface to the desired flight condition. Reversing the input effort moves the control surface in the opposite direction.

Manual Control

The control system from the cockpit is connected by a rod across the power transmission quadrant to the control actuating system. During manual operation, the pilot's effort is transmitted from the control wheel through this direct linkage to the control surface. Those aircraft which do not have the manual reversion system may have as many as three sources of hydraulic power-primary, back-up and auxiliary. Any or all of the primary controls may be operated by these systems.

Gust Lock

A cam on the control quadrant shaft engages a spring-loaded roller for the purpose of centering and neutralizing the controls with the hydraulic system off (aircraft parked). Pressure is trapped in the actuators and since the controls are neutralized by the cam and roller, no movement of the control surfaces is permitted.

CABLE GUIDES

Cable guides (figure 2–59) consist primarily of **fairleads, pressure seals, and pulleys.**

A fairlead may be made from a nonmetallic material, such as phenolic or a metallic material such as soft aluminum. The fairlead completely encircles the cable where it passes through holes in bulkheads or other metal parts. Fairleads are used to guide cables

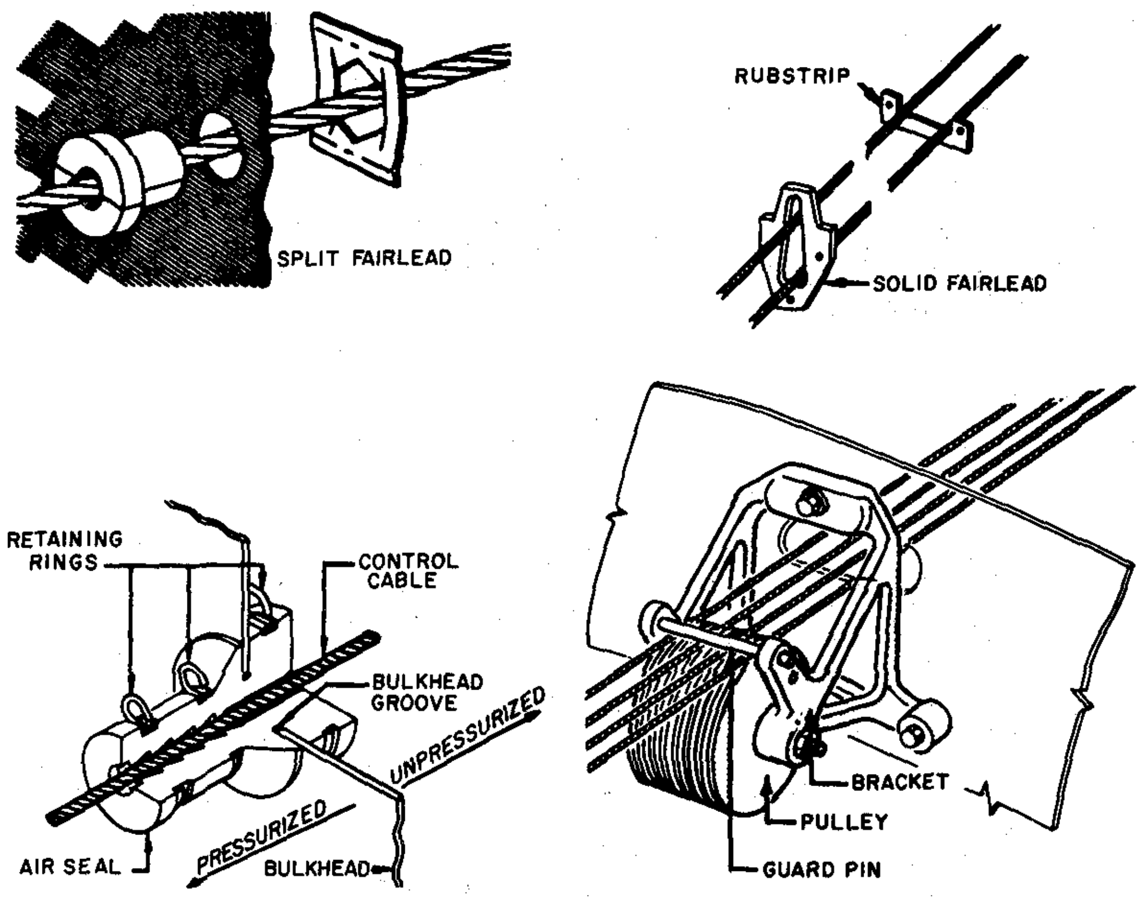


FIGURE 2–59. Cable guides.

in a straight line through or between structural members of the aircraft. Fairleads should never deflect the alignment of a cable more than 3° from a straight line.

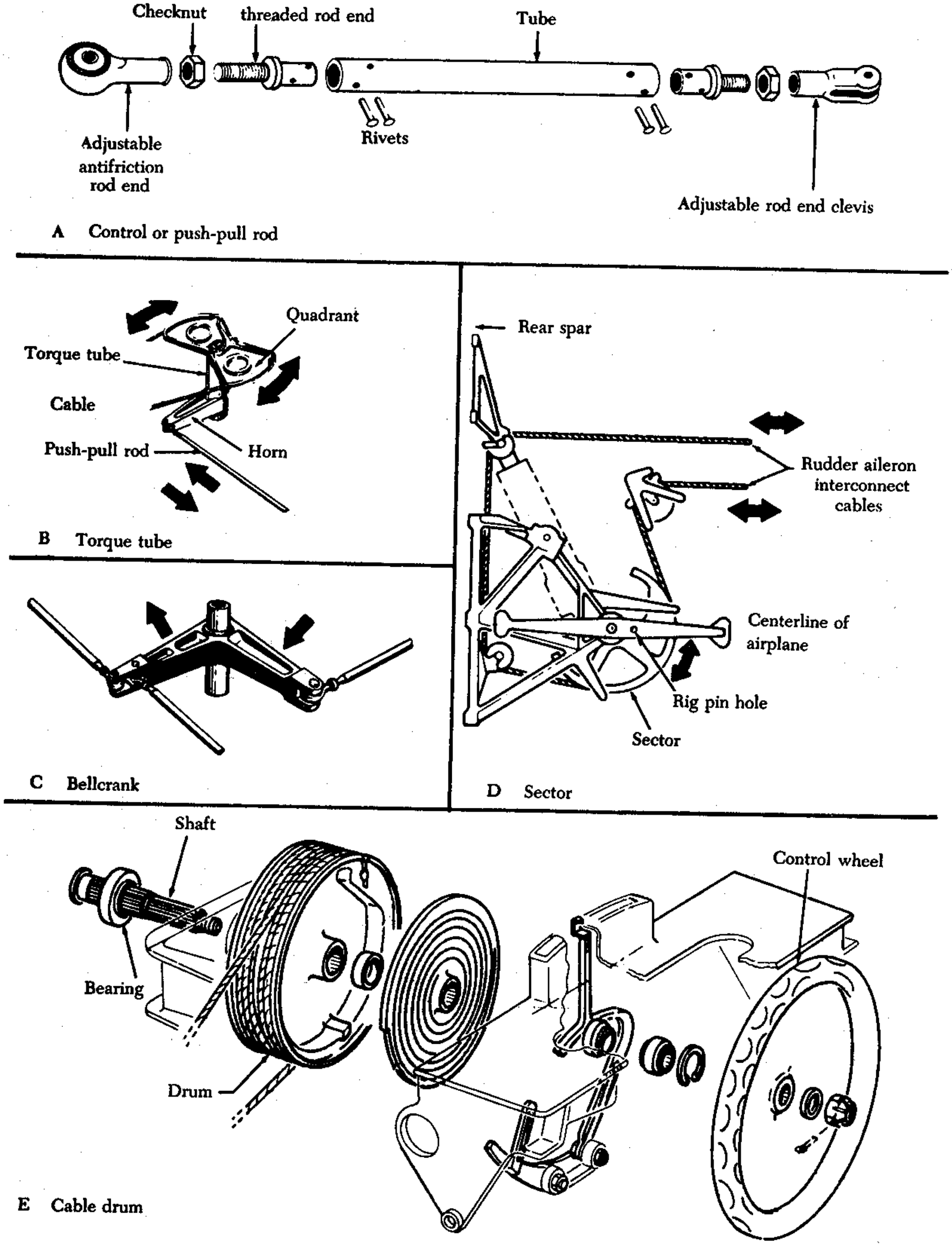


FIGURE 2-60. Flight control system mechanical linkages.

Pressure seals are installed where cables (or rods) move through pressure bulkheads. The seal grips tightly enough to prevent excess air pressure loss but not enough to hinder movement of the cable. Pressure seals should be inspected at regular intervals to determine that the retaining rings are in place. If a retaining ring comes off, it may slide along the cable and cause jamming of a pulley.

Pulleys are used to guide cables and also to change the direction of cable movement. Pulley bearings are sealed, and need no lubrication other than the lubrication done at the factory. Brackets fastened to the structure of the aircraft support the pulleys. Cables passing over pulleys are kept in place by guards. The guards are close-fitting to prevent jamming or to prevent the cables from slipping off when they slacken due to temperature variations.

MECHANICAL LINKAGE

Various mechanical linkages connect the cockpit controls to control cables and surface controls. These devices either transmit motion or change the direction of motion of the control system. The linkage consists primarily of control (push-pull) rods, torque tubes, quadrants, sectors, bellcranks, and cable drums.

Control rods are used as links in flight control systems to give a push-pull motion. They may be adjusted at one or both ends. View A of figure 2–60 shows the parts of a control rod. Notice that it consists of a tube having threaded rod ends. An adjustable antifriction rod end, or rod end clevis, attaches at each end of the tube. The rod end, or clevis, permits attachment of the tube to flight control system parts. The checknut, when tightened, prevents the rod end or clevis from loosening.

Control rods should be perfectly straight, unless designed to be otherwise, when they are installed. The bellcrank to which they are attached should be checked for freedom of movement before and after attaching the control rods. The assembly as a whole should be checked for correct alignment. When the rod is fitted with self-aligning bearings, free rotational movement of the rods must be obtained in all positions.

It is possible for control rods fitted with bearings to become disconnected because of failure of the peening that retains the ball races in the rod end. This can be avoided by installing the control rods so that the flange of the rod end is interposed between the ball race and the anchored end of the attaching pin or bolt as shown in figure 2–61.

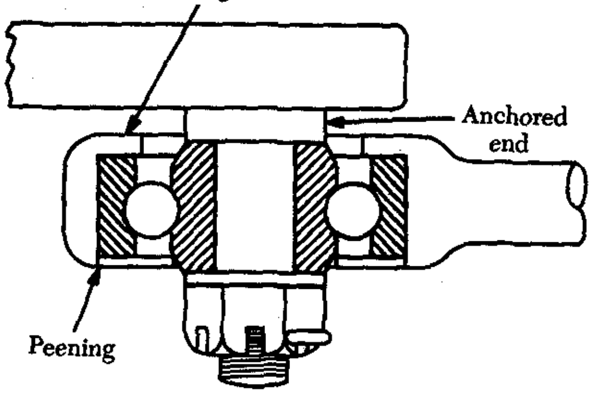


FIGURE 2–61. Rod end flange interposed between the bearing race and the end of the attaching bolt.

Another alternative is to place a washer, having a larger diameter than the hole in the flange, under the retaining nut on the end of the attaching pin or bolt.

TORQUE TUBES

Where an angular or twisting motion is needed in a control system, a torque tube is installed. View B of figure 2–60 shows how a torque tube is used to transmit motion in opposite directions.

Quadrants, bellcranks, sectors, and drums change direction of motion and transmit motion to parts such as control rods, cables, and torque tubes. The quadrant shown in figure 2–60B is typical of flight control system linkages used by various manufacturers. Figures 2–60C and 2–60D illustrate a bellcrank and a sector. View E illustrates a cable drum. Cable drums are used primarily in trim tab systems. As the trim tab control wheel is moved clockwise or counterclockwise, the cable drum winds or unwinds to actuate the trim tab cables.

STOPS

Adjustable and nonadjustable stops (whichever the case requires) are used to limit the throw-range or travel movement of the ailerons, elevator, and rudder. Usually there are two sets of stops for each of the three main control surfaces, one set being located at the control surface, either in the snubber cylinders or as structural stops (figure 2–62), and the other at the cockpit control. Either of these may serve as the actual limit stop. However, those situated at the control surface usually perform this function. The other stops do not normally contact each other, but are adjusted to a definite clearance when the control surface is at the full extent of its travel. These work as over-ride stops to prevent stretching of cables and damage to the control system during violent maneuvers. When rigging control systems, refer to the applicable maintenance manual for the sequence of steps for adjusting these stops to limit the control surface travel.

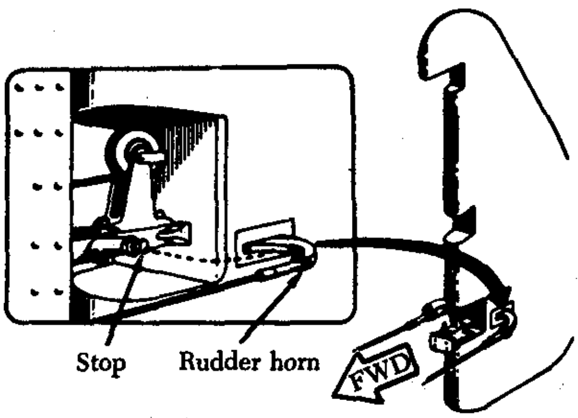


FIGURE 2–62. Adjustable rudder stops.

CONTROL SURFACE SNUBBERS AND LOCKING DEVICES

Various types of devices are in use to lock the control surfaces when the aircraft is parked or moored. Locking devices prevent damage to the control surfaces and their linkages from gusts and high-velocity winds. Common devices that are in use are the internal locking brake (sector brake) spring-loaded plunger, and external control surface locks.

Internal Locking Devices

The internal locking device is used to secure the ailerons, rudder, and elevator in their neutral positions. The locking device is usually operated through a cable system by a spring-loaded plunger (pin) that engages a hole in the control surface mechanical linkage to lock the surface. A spring connected to the pin forces it back to the unlock position when the cockpit control lever is placed in the "unlock" position. An over-center toggle linkage is used on some other type aircraft to lock the control surfaces.

Control surface locking systems are usually so designed that the throttles cannot be advanced until the control surfaces are unlocked. This prevents taking off with the control surfaces in the locked position.

A typical control lock for small aircraft consists of a metal tube that is installed to lock the control wheel and rudder pedals to an attachment in the cockpit. Such a system is illustrated in figure 2–63.

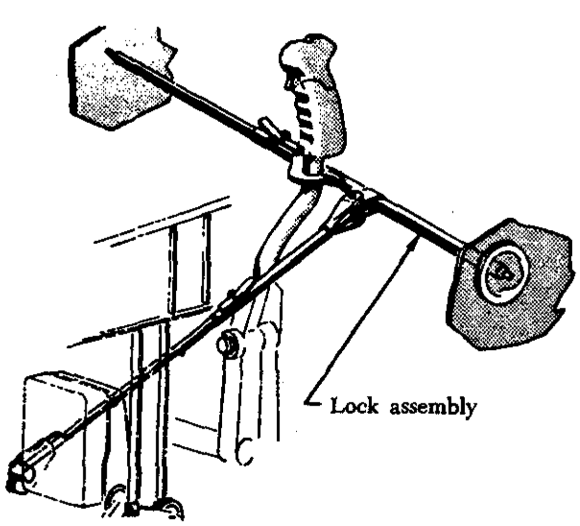


FIGURE 2–63. Typical control lock assembly for small aircraft.

Control Surface Snubbers

Hydraulic booster units are used on some aircraft to move the control surfaces. The surfaces are usually protected from wind gusts by snubbers incorporated into the booster unit. On some aircraft an auxiliary snubber cylinder is connected directly to the surface to provide protection. The snubbers hydraulically check or cushion control surface movement when the aircraft is parked. This prevents wind gusts from slamming the control surfaces into their stops and possibly causing damage.

External Control Surface Locks

External control surface locks are in the form of channeled wood blocks. The channeled wood blocks slide into the openings between the ends of the movable surfaces and the aircraft structure. This locks the surfaces in neutral. When not in use, these locks are stowed within the aircraft.

Tension Regulators

Cable tension regulators are used in some flight control systems because there is considerable difference in temperature expansion of the aluminum aircraft structure and the steel control cables. Some large aircraft incorporate tension regulators in the control cable systems to automatically maintain a given cable tension. The unit consists of a compression spring and a locking mechanism which allows the spring to make correction in the system only when the cable system is in neutral.

AIRCRAFT RIGGING

Control surfaces should move a certain distance in either direction from the neutral position. These movements must be synchronized with the movement of the cockpit controls. The flight control system must be adjusted (rigged) to obtain these requirements.

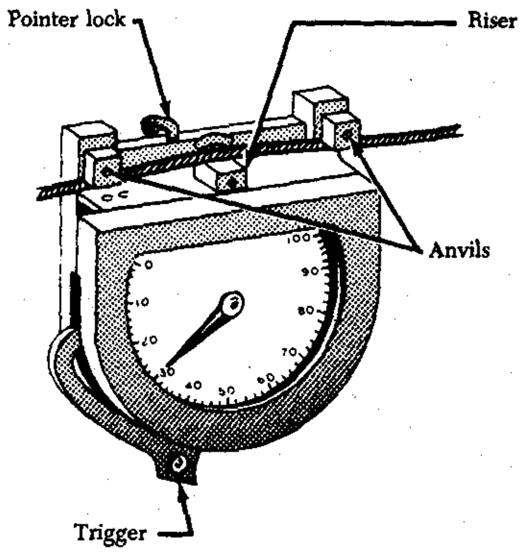
Generally speaking, the rigging consists of the following: (1) Positioning the flight control system in neutral and temporarily locking it there with rig pins or blocks, and (2) adjusting surface travel, system cable tension, linkages, and adjustable stops to the aircraft manufacturer's specifications.

When rigging flight control systems, certain items of rigging equipment are needed. Primarily, this equipment consists of tensiometers, cable rigging tension charts, protractors, rigging fixtures, contour templates, and rulers.

Measuring Cable Tension

To determine the amount of tension on a cable, a tensiometer is used. When properly maintained, a tensiometer is 98% accurate. Cable tension is determined by measuring the amount of force needed to make an offset in the cable between two hardened steel blocks, called anvils. A riser or plunger is pressed against the cable to form the offset. Several manufacturers make a variety of tensiometers, each type designed for different kinds of cable, cable sizes, and cable tensions.

One type of tensiometer is illustrated in figure 2–64. With the trigger lowered, place the cable to be tested under the two anvils. Then close the trigger (move it up). Movement of the trigger pushes up the riser, which pushes the cable at right angles to the two clamping points under the anvils. The force that is required to do this is indicated by the dial pointer. As the sample chart beneath the illustration shows, different numbered risers are used with different size cables. Each riser has an identifying number and is easily inserted into the tensiometer.



Sample only

Example

No. 1			Riser	No. 2		No. 3
Dia. 1/16	3/32	1/8	Tension Lb.	5/32	3/16	7/32 1/4
12	16	21	30	12	20	
19	23	29	40	17	26	
25	30	36	50	22	32	
31	36	43	60	26	37	
36	42	50	70	30	42	
41	48	57	80	34	47	
46	54	63	90	38	52	
51	60	69	100	42	56	
			110	46	60	
			120	50	64	

FIGURE 2–64. Tensiometer.

In addition, each tensiometer has a calibration table (figure 2–64) which is used to convert the dial reading to pounds. (The calibration table is very similar to the sample chart shown below the illustration.) The dial reading is converted to pounds of tension as follows. Using a No. 2 riser (figure 2–64) to measure the tension of a 5/32-in. diameter cable a reading of "30" is obtained. The actual tension (see calibration table) of the cable is 70 lbs. Observing the chart, also notice that a No. 1 riser is used with 1/16-, 3/32-, and 1/8-in. cable. Since the tensiometer is not designed for use in measuring 7/32- or 1/4-in. cable, no values are shown in the No. 3 riser column of the chart.

When taking a reading, it may be difficult to see the dial. Therefore, a pointer lock is present on the tensiometer. Push it in to lock the pointer. Then remove the tensiometer from the cable and observe the reading. After observing the reading, pull the lock out and the pointer will return to zero.

Cable rigging tension charts (figure 2–65) are graphic tools used to compensate for temperature variations. They are used when establishing cable tensions in flight control systems, landing gear systems, or any other cable-operated systems.

To use the chart, determine the size of the cable that is to be adjusted and the ambient air temperature. For example, assume that the cable size is 1/8-in. in diameter, that it is a 7 x 19 cable, and the ambient air temperature is 85° F. Follow the 85° F. line upward to where it intersects the curve for 1/8-in. cable. Extend a horizontal line from the point of intersection to the right edge of the chart. The value at this point indicates the tension (rigging load in pounds) to establish on the cable. The tension for this example is 70 lbs.

Surface Travel Measurement

The tools for measuring surface travel primarily include protractors, rigging fixtures, contour templates, and rulers. These tools are used when rigging flight control systems to assure that the desired travel has been obtained.

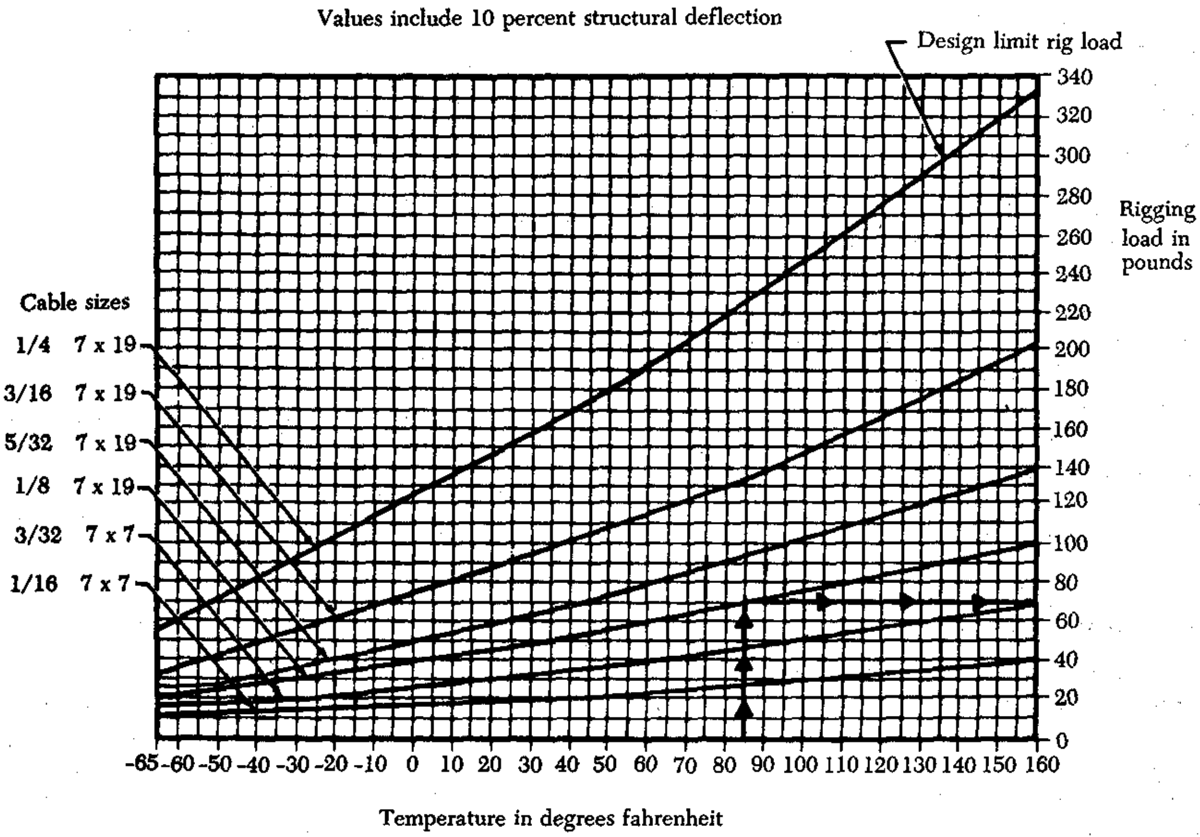


FIGURE 2–65. Typical cable rigging chart.

Protractors are tools for measuring angles in degrees. Various types of protractors are used to determine the travel of flight control surfaces. One protractor that can be used to measure aileron, elevator, or wing flap travel is the universal propeller protractor. Notice that this protractor (figure 2–66) is made up of a frame, a disk, a ring, and two spirit levels. The disk and ring turn independently of each other and of the frame. (The corner spirit level is used to position the frame vertically when measuring propeller blade angle.) The center spirit level is used to position the disk when measuring control surface travel. A disk-to-ring lock is provided to secure the disk and ring together when the zero on the ring vernier scale and the zero on the disk degree scale align. The ring-to-frame lock prevents the ring from moving when the disk is moved. Note that they start at the same point and advance in opposite directions. A double 10-part vernier is marked on the ring.

The procedure to use for operating the protractor to measure control surface travel is shown at the bottom of figure 2–66.

Rigging Fixtures and Contour Templates

Rigging fixtures and templates are special tools (gages) designed by the manufacturer to measure control surface travel. Markings on the fixture or template indicate desired control surface travel.

Rulers

In many instances the aircraft manufacturer gives the travel of a particular control surface in degrees and inches. If the travel in inches is provided, a ruler can be used to measure surface travel in inches.

RIGGING CHECKS

The purpose of this section is to explain the methods of checking the relative alignment and adjustment of an aircraft's main structural components. It is not intended to imply that the procedures are exactly as they may be in a particular aircraft. When rigging an aircraft, always follow the procedures and methods specified by the aircraft manufacturer.

Structural Alignment

The position or angle of the main structural components is related to a longitudinal datum line parallel to the aircraft center line and a lateral datum line parallel to a line joining the wing tips. Before checking the position or angle of the main components, the aircraft should be leveled.

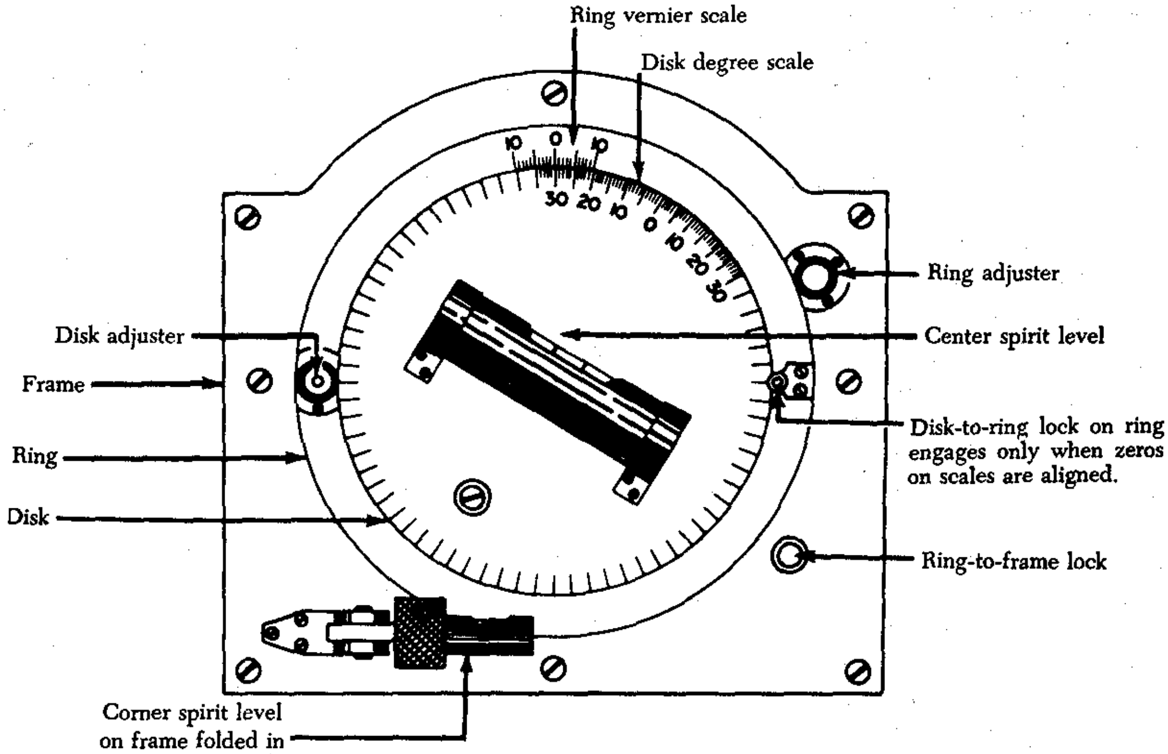
Small aircraft usually have fixed pegs or blocks attached to the fuselage parallel to or coincident with the datum lines. A spirit level and a straight edge are rested across the pegs or blocks to check the level of the aircraft. This method of checking aircraft level also applies to many of the larger types of aircraft. However, the grid method is sometimes used on large aircraft. The grid plate (figure 2–67) is a permanent fixture installed on the aircraft floor or supporting structure. When the aircraft is to be leveled, a plumb bob is suspended from a predetermined position in the ceiling of the aircraft over the grid plate. The adjustments to the jacks necessary to level the aircraft are indicated on the grid scale. The aircraft is level when the plumb bob is suspended over the center point of the grid.

Certain precautions must be observed in all instances. Normally, rigging and alignment checks should not be undertaken in the open. If this cannot be avoided, the aircraft should be positioned with the nose into the wind.

The weight and loading of the aircraft should be exactly as described in the manufacturer's manual. In all cases, the aircraft should not be jacked until it is ensured that the maximum jacking weight (if any) specified by the manufacturer is not exceeded.

With a few exceptions, the dihedral and incidence angles of conventional modern aircraft cannot be adjusted. Some manufacturers permit adjusting the wing angle of incidence to correct for a wing-heavy condition. The dihedral and incidence angles should be checked after hard landings or after experiencing abnormal flight loads to ensure that the components are not distorted and that the angles are within the specified limits.

There are several methods for checking structural alignment and rigging angles. Special rigging boards which incorporate, or on which can be placed, a special instrument (spirit level or clinometer) for determining the angle are used on some aircraft. On a number of aircraft the alignment is checked using a transit and plumb bobs or a theo-



1 With disk-to-ring lock in the deep slot, turn disk adjuster to lock disk to ring.

2 Move control surface to neutral. Place protractor on control surface and turn ring adjuster to center bubble in center spirit level (ring must be unlocked from frame).

3 Lock ring to frame with ring-to-frame lock.

4 Move control surface to extreme limit of movement

5 Unlock disk from ring with disk-to-ring lock.

6 Turn disk adjuster to center bubble in center spirit level.

7 Read surface travel in degrees on disk and tenths of a degree on vernier scale.

FIGURE 2–66. Using the universal propeller protractor to measure control surface travel.

dolite and sighting rods. The particular equipment to use is usually specified in the manufacturer's manuals.

When checking alignment, a suitable sequence should be developed and followed to be certain that the checks are made at all the positions specified. The alignment checks specified usually include:

(1) Wing dihedral angle.
(2) Wing incidence angle.
(3) Engine alignment.
(4) Horizontal stabilizer incidence.
(5) Horizontal stabilizer dihedral.
(6) Verticality of the fin.
(7) A symmetry check.

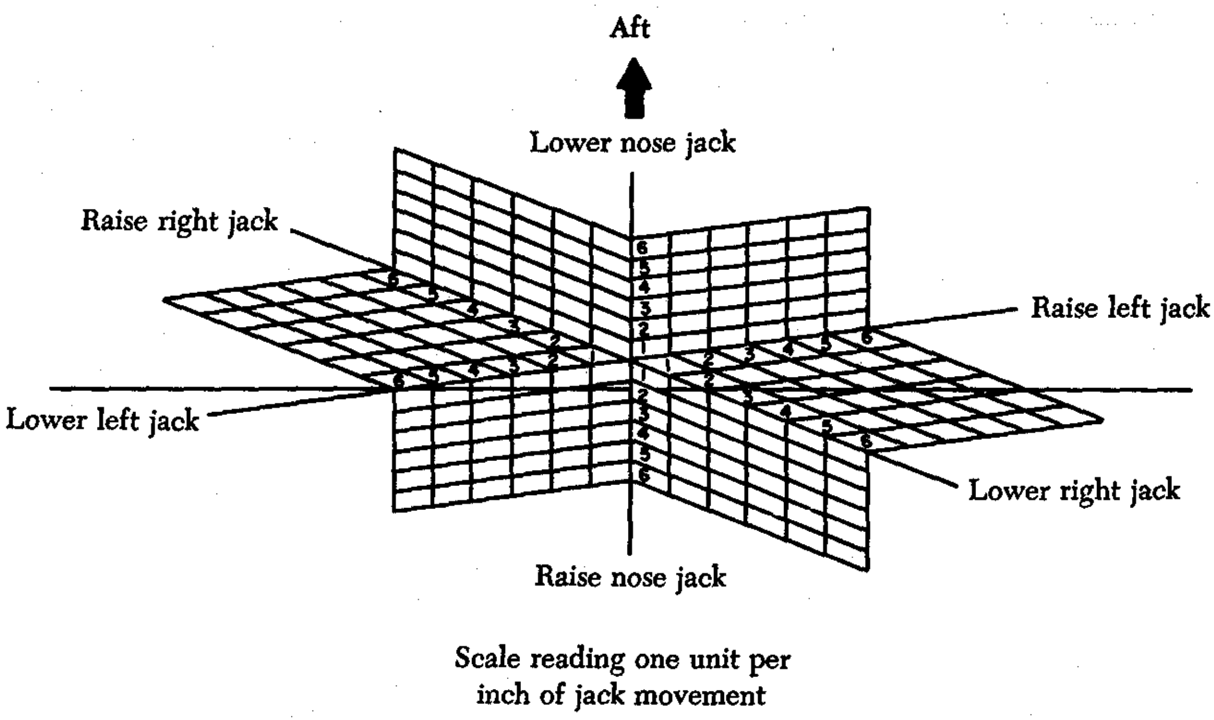


FIGURE 2-67. Typical grid plate.

Checking Dihedral

The dihedral angle should be checked in the specified positions using the special boards provided by the aircraft manufacturer. If no such boards are available, a straight edge and a clinometer can be used. The methods for checking dihedral are shown in figure 2-68.

It is important that the dihedral be checked at the positions specified by the manufacturer. Certain portions of the wings or horizontal stabilizer may sometimes be horizontal or, on rare occasions, anhedral angles may be present.

Checking Incidence

Incidence is usually checked in at least two specified positions on the surface of the wing to ensure

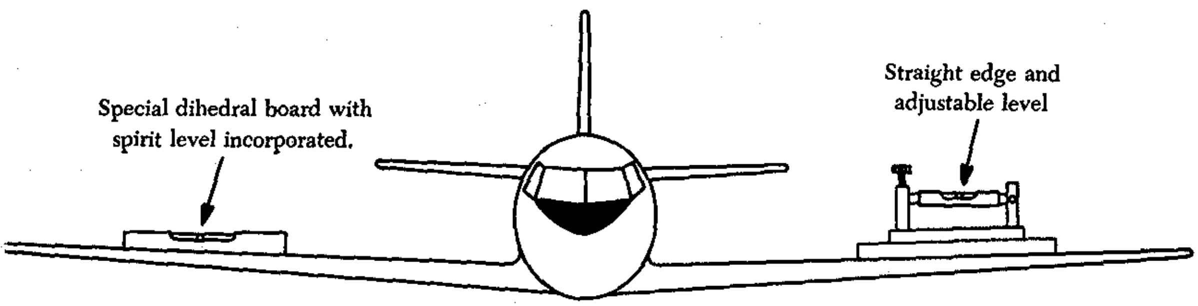


FIGURE 2-68. Checking dihedral.

that the wing is free from twist. A variety of incidence boards are used to check the incidence angle. Some have stops at the forward edge which must be placed in contact with the leading edge of the wing. Others are equipped with location pegs which fit into some specified part of the structure. The purpose in either case is to ensure that the board is fitted in exactly the position intended. In most instances, the boards are kept clear of the wing contour by short extensions attached to the board. A typical incidence board is shown in figure 2–69.

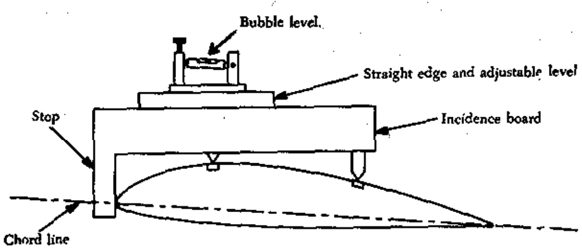


FIGURE 2–69. A typical incidence board.

When used, the board is placed at the specified locations on the surface being checked. If the incidence angle is correct, a clinometer on top of the board will read zero, or within a specified tolerance of zero. Modifications to the areas where incidence boards are located can affect the reading. For example, if leading-edge deicer boots have been installed, this will affect the position taken by a board having a leading edge stop.

Checking Fin Verticality

After the rigging of the horizontal stabilizer has been checked, the verticality of the vertical stabilizer relative to the lateral datum can be checked. The measurements are taken from a given point on either side of the top of the fin to a given point on the left and right horizontal stabilizers (figure 2–70). The measurements should be similar within prescribed limits. When it is necessary to check the alignment of the rudder hinges, remove the rudder and pass a plumb bob line through the rudder hinge attachment holes. The line should pass centrally through all the holes. It should be noted that some aircraft have the leading edge of the vertical fin offset to the longitudinal center line to counteract engine torque.

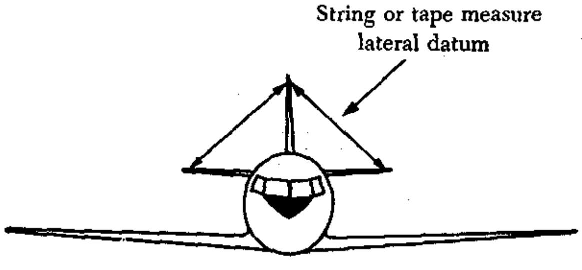


FIGURE 2–70. Checking fin verticality.

Checking Engine Alignment

Engines are usually mounted with the thrust line parallel to the horizontal longitudinal plane of symmetry. However, this is not always true when the engines are mounted on the wings. Checking to ensure that the position of the engines, including any degree of offset, is correct depends largely on the type of mounting. Generally, the check entails a measurement from the center line of the mounting to the longitudinal center line of the fuselage (figure 2–71) at the point specified in the applicable manual.

Symmetry Check

The principle of a typical symmetry check is illustrated in figure 2–71. The precise figures, tolerances and checkpoints for a particular aircraft will be found in the applicable service or maintenance manual.

On small aircraft the measurements between points are usually taken using a steel tape. When measuring long distances, it is suggested that a spring scale be used with the tape to obtain equal tension. A 5-lb. pull is usually sufficient.

Where large aircraft are concerned, the positions where the dimensions are to be taken are usually chalked on the floor. This is done by suspending a plumb bob from the checkpoints, and marking the floor immediately under the point of each plumb bob. The measurements are then taken between the center of each marking.

ADJUSTMENT OF CONTROL SURFACES

In order for a control system to function properly, it must be correctly adjusted. Correctly rigged control surfaces will move through a prescribed arc (surface-throw) and be synchronized with the movement of the cockpit controls.

Rigging any system requires that the step-by-step procedures be followed as outlined in the aircraft maintenance manual. Although the complete rigging procedure for most aircraft is of a detailed nature that requires several adjustments, the basic method follows three steps:

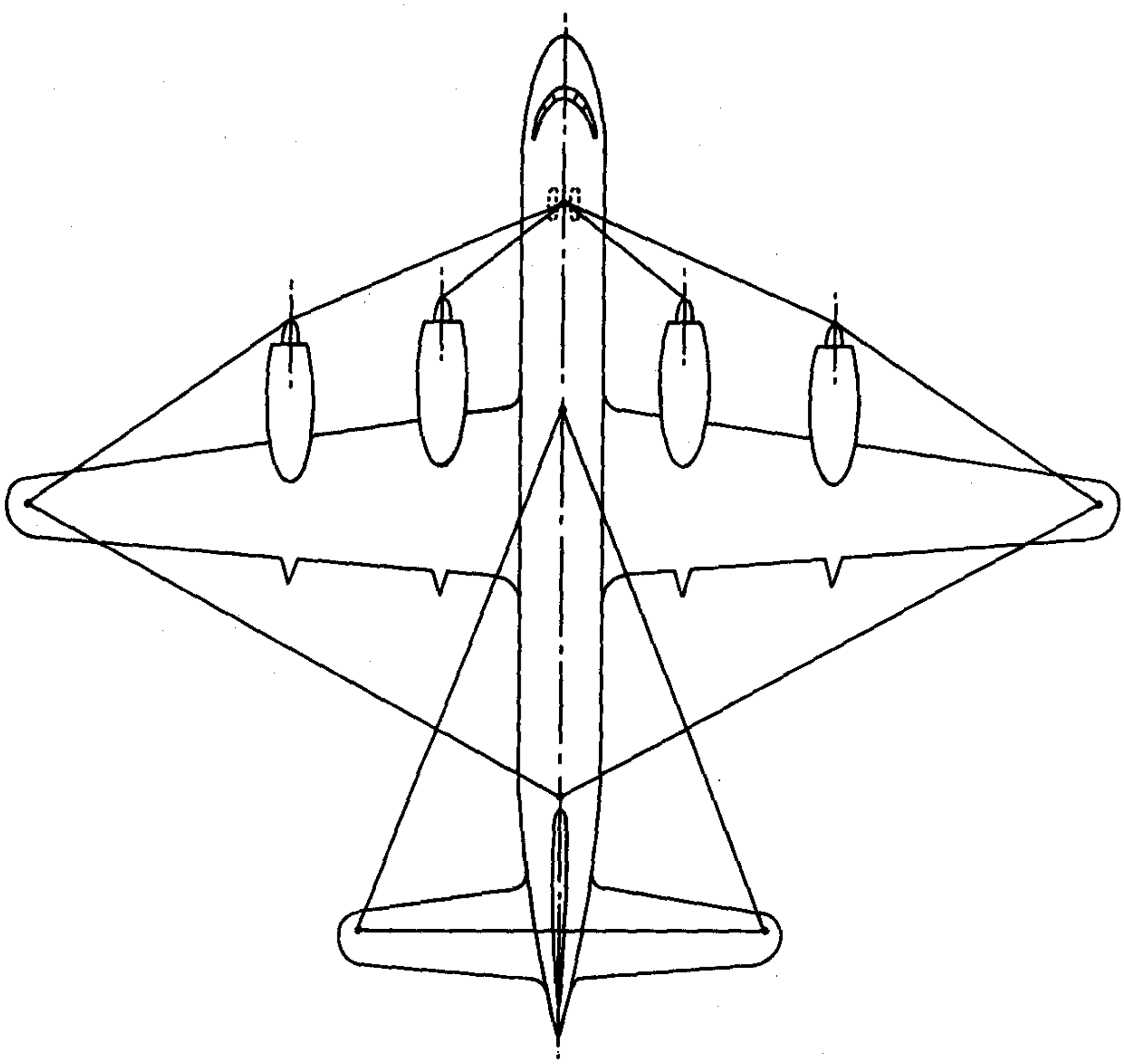


FIGURE 2-71. A typical method of checking aircraft symmetry.

(1) Lock the cockpit control, bellcranks, and the control surfaces in the neutral position.

(2) Adjust the cable tension, maintaining the rudder, elevators, or ailerons in the neutral position.

(3) Adjust the control stops to limit the control surface travel to the dimensions given for the aircraft being rigged.

The range of movement of the controls and control surfaces should be checked in both directions from neutral.

The rigging of the trim tab systems is performed in a similar manner. The trim tab control is set to the neutral (no trim) position, and the surface tab is usually adjusted to streamline with the control surface. However, on some aircraft the trim tabs may be offset a degree or two from streamline when in the "neutral" position. After the tab and tab control are in the neutral position, adjust the control cable tension.

Pins, usually called rig pins, are sometimes used to simplify the setting of pulleys, levers, bellcranks, etc., in their neutral positions. A rig pin is a small metallic pin or clip. When rig pins are not provided, the neutral positions can be established by means of alignment marks, by special templates, or by taking linear measurements.

If the final alignment and adjustment of a system are correct, it should be possible to withdraw the rigging pins easily. Any undue tightness of the pins in the rigging holes indicates incorrect tensioning or misalignment of the system.

After a system has been adjusted, the full and synchronized movement of the controls should be checked. When checking the range of movement of the control surface, the controls must be operated from the cockpit and not by moving the control surfaces. During the checking of control surface travel, ensure that chains, cables, etc., have not reached the limit of their travel when the controls are against their respective stops. Where dual controls are installed, they must be synchronized and function satisfactorily when operated from both positions.

Trim tabs and other tabs should be checked in a manner similar to the main control surfaces. The tab position indicator must be checked to see that it functions correctly. If jackscrews are used to actuate the trim tab, check to see that they are not extended beyond the specified limits when the tab is in its extreme positions.

After determining that the control system functions properly and is correctly rigged, it should be thoroughly inspected to determine that the system is correctly assembled, and will operate freely over the specified range of movement. Make certain that all turnbuckles, rod ends, and attaching nuts and bolts are correctly safetied.

HELICOPTER RIGGING

The flight control units located in the cockpit (figure 2–72) of all helicopters are very nearly the same. All helicopters have either one or two of each of the following: (1) Collective pitch control, (2) cyclic pitch control, and (3) directional control pedals. Basically, these units do the same things, regardless of the type of helicopter on which they are installed. But this is where most of the similarity ends. The operation of the systems in which these units are installed varies greatly according to the helicopter model.

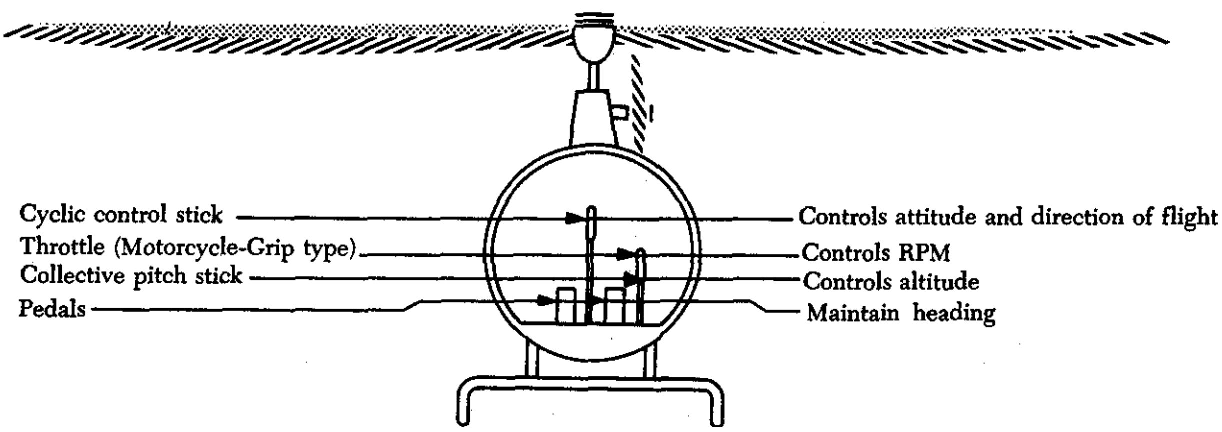


FIGURE 2–72. Controls of the helicopter and the principal function of each.

Rigging the helicopter coordinates the movements of the flight controls and establishes the relationship between the main rotor and its controls and between the tail rotor and its controls. Rigging is not a difficult job, but it requires great precision and attention to detail. Strict adherence to rigging procedures is a must. Adjustments, clearances, and tolerances must be exact.

Rigging of the various flight control systems can be broken down into three major steps.

(1) Step one consists of placing the control system in a particular position; holding it in position with pins, clamps, or jigs; and adjusting the various linkages to fit the immobilized control component.

(2) Step two consists of placing the control surfaces in a specific reference position; using a rigging jig (figure 2–73), a precision bubble protractor, or a spirit level to check the angular difference between the control surface and some fixed surface on the aircraft.

(3) Step three consists of setting the maximum range of travel of the various components.

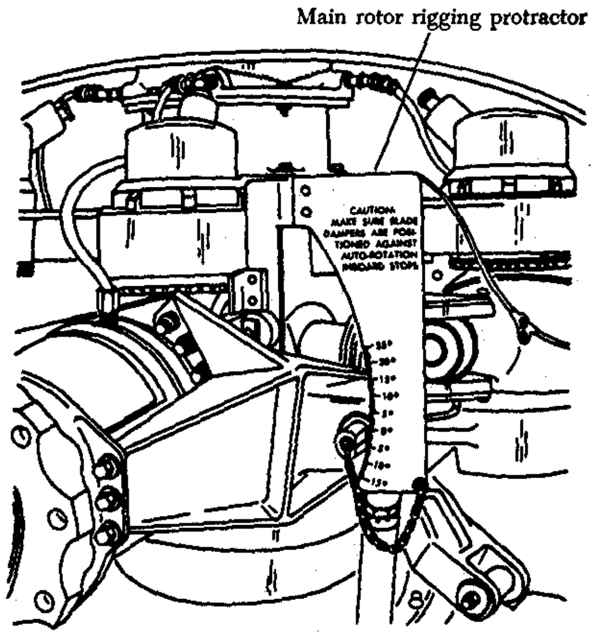


FIGURE 2–73. A typical rigging protractor.

This adjustment limits the physical movement of the control system.

After completion of the static rigging, a functional check of the flight control system must be accomplished. The nature of the functional check will vary with the type of rotorcraft and system concerned, but usually includes determining that:

(1) The direction of movement of the main and tail rotor blades is correct in relation to movement of the pilot's controls.

(2) The operation of interconnected control systems (engine throttle and collective pitch) are properly coordinated.

(3) The range of movement and neutral position of the pilot's controls are correct.

(4) The maximum and minimum pitch angles of the main rotor blades are within specified limits. This includes checking the fore-and-aft and lateral cyclic pitch and collective pitch blade angles.

(5) The tracking of the main rotor blades is correct.

(6) In the case of multi-rotor aircraft, the rigging and movement of the rotor blades are synchronized.

(7) When tabs are provided on main rotor blades, they are correctly set.

(8) The neutral, maximum and minimum pitch angles and coning angles of the tail rotor blades are correct.

(9) When dual controls are provided, they function correctly and in synchronization.

Upon completion of rigging, a thorough check should be made of all attaching, securing, and pivot points. All bolts, nuts, and rod ends should be properly secured and safetied.

Blade Tracking

When the main rotor blades do not "cone" by the same amount during rotation, it is referred to as "out of track." This may result in excessive vibration at the control column. Blade tracking is the process of determining the positions of the tips of the rotor blade relative to each other while the rotor head is turning, and of determining the corrections necessary to hold these positions within certain tolerances. Tracking shows only the relative position of the blades, not their path of flight. The blades should all track one another as closely as possible. The purpose of blade tracking is to bring the tips of all blades into the same tip path throughout their entire cycle of rotation.

In order to track rotor blades with minimum time and maximum accuracy, the correct equipment must be available. The equipment generally used to track blades includes:

(1) Tracking flag with flag material.

(2) Grease pencils or colored chalk.

(3) Suitable marking material.

(4) Reflectors and tracking lights (figure 2–74).

(5) Tracking stick.

(6) Trim-tab bending tool.

(7) Trim-tab angle indicator.

Before starting a blade tracking operation, new or recently overhauled blades should be checked for proper incidence. Trim tabs should be set at zero on new or overhauled blades. Trim tabs of blades in service should not be altered until blade track has been determined.

One means of tracking is the flag tracking method (figure 2–75). The blade tips are marked with chalk or grease pencil. Each blade tip should be marked with a different color so that it will be easy to determine the relationship of the tips of the rotor blades to each other. This method can be used on all types of helicopters that do not have jet propulsion at the blade tips. The man holding the flag faces in the direction of blade rotation, watching the retreating blades. Facing away from the oncoming blades permits the flag holder to observe the blades as they come in contact with the flag.

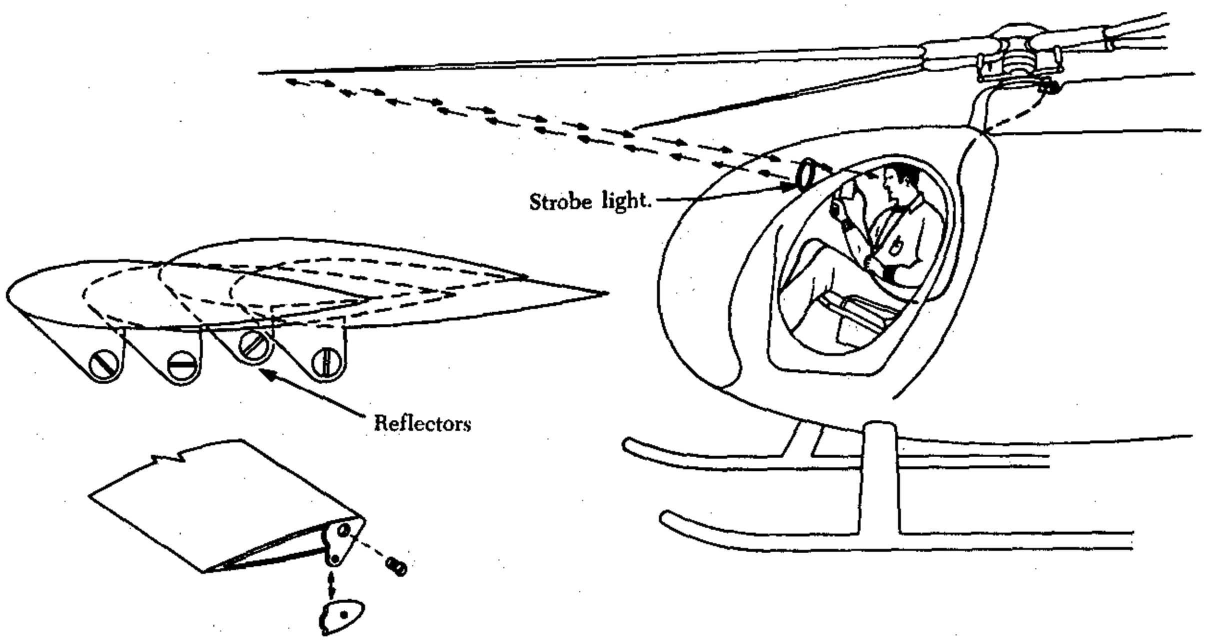


FIGURE 2-74. Blade tracking with strobe light.

The angle of the flag to the chord of the blade is important. If the angle is too great, the marks will be long and the flag will flutter excessively. If the angle is too straight, the blade may cut the flag. The most satisfactory angle is about 80° to the chord line of the blade. The marks on the flag will then be approximately 3/16 in. to 1/4 in. long. The flag method of tracking can be used not only to ascertain the relative positions of the blades but also the flight characteristics of the blades at different r.p.m. and power settings.

In order to plot the flight characteristics of a set of blades, it is necessary to take a trace at different r.p.m. settings and record the results. A minimum of three traces is necessary to produce a satisfactory plot. Four traces are desirable to produce a plot on heads having three or more rotor blades. When the tracking plot is completed, one blade is chosen as a reference blade. Usually, the reference blade is the center blade of a plot on a multi-blade rotor system and the lower blade on a two-blade rotor system. If the center or lower blade of a plot shows unusual flight characteristics, another blade may be chosen as the reference blade. A blade track that rises with an increase in r.p.m. is a climbing blade; one that lowers with increase of r.p.m. or power is a diving blade. When a climbing blade and a diving blade cross, it is termed a crossover. Because of the climbing and diving tendencies of imporperly rigged blades, it is possible to have all blades at a common point at certain r.p.m. and power settings, but out of track at other r.p.m. or power settings.

The most common error in blade tracking is to bring the blades into track with trim tabs at cruise r.p.m. only. The blades may then be at the meeting point of a crossover and will spread at different r.p.m. power settings, or forward speed; an out-of-track condition will result. The correct tracking procedure is to maintain a constant blade spread at all r.p.m. power settings and flight speeds. A constant spread can be held only by proper adjustment of trim tabs. After a constant spread has been established with trim tabs, it is necessary to bring the blade tips into a single path of rotation with the pitch links. Bending the trim tabs up will raise the blade and bending them down will lower the blade. Bending of trim tabs should be kept to a minimum because tab angle produces excessive drag on the blades. The setting of the tabs on main rotor blades (if provided) should be checked to eliminate out-of-balance moments which will apply torque to the rotor blades. The tab setting is checked for correctness by running the rotor at the prescribed speed and ensuring that the cyclic-pitch control column remains stationary. Out-of-balance moments impart a stirring motion to the column.

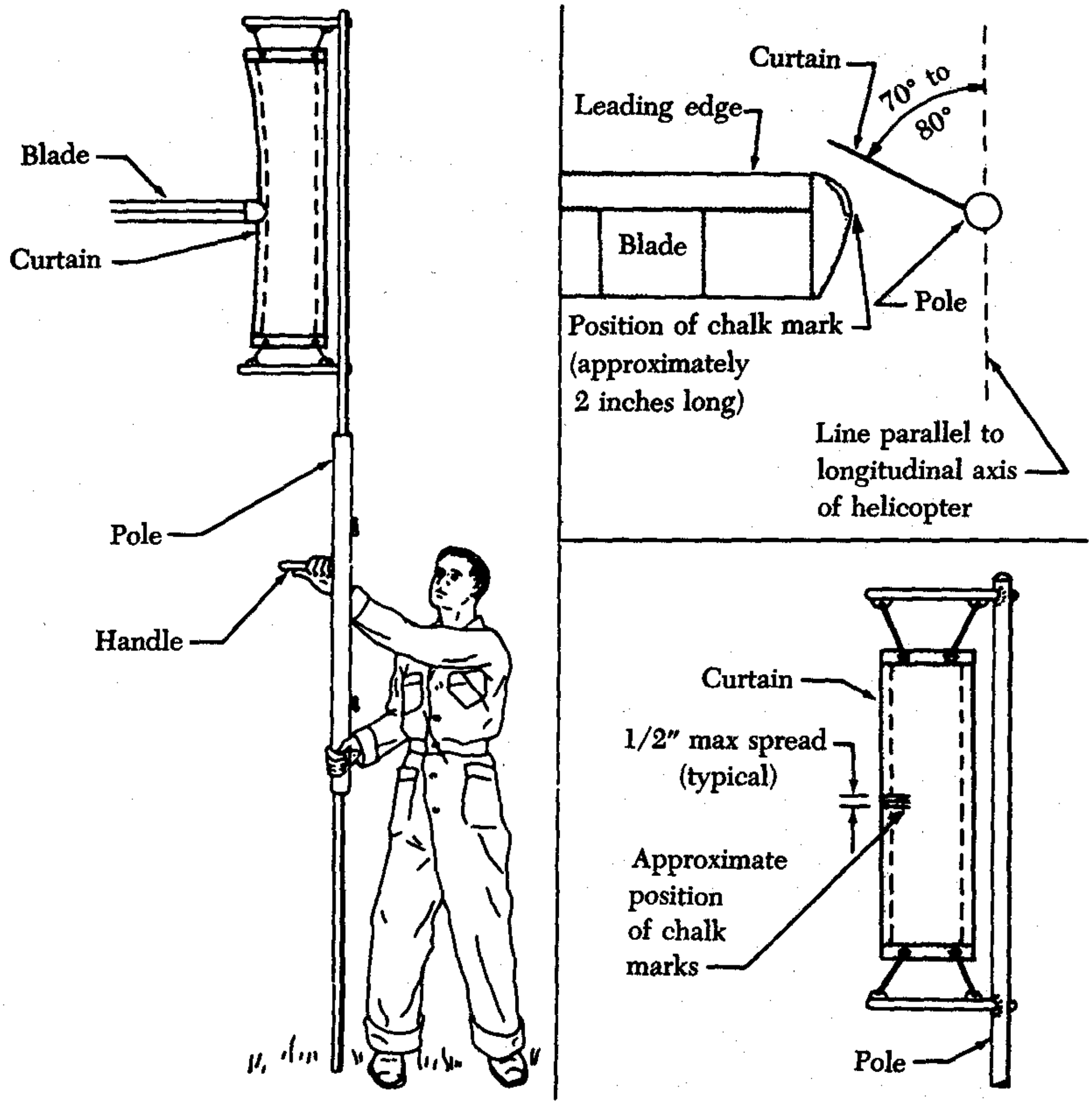


FIGURE 2–75. Tracking.

PRINCIPLES OF BALANCING OR RE-BALANCING

The principles that are essential in the balancing or re-balancing of the control surfaces are not too difficult to understand if some simple comparison is used. For example, a seesaw that is out of balance may be compared to a control surface that does not have balance weights installed, as in figure 2–76. From this illustration, it is easy to understand how a control surface is naturally tail (trailing edge) heavy.

It is this out-of-balance condition that can cause a damaging flutter or buffeting of an aircraft and therefore must be eliminated. This is best accomplished by adding weights either inside or on the leading edge of the tabs, ailerons, or in the proper location on the balance panels. When this is done properly, a balanced condition exists and can be compared to the seesaw with a child sitting on the short end of the plank.

The effects of moments on control surfaces can be easily understood by a closer observation and study of a seesaw and two children of different weights

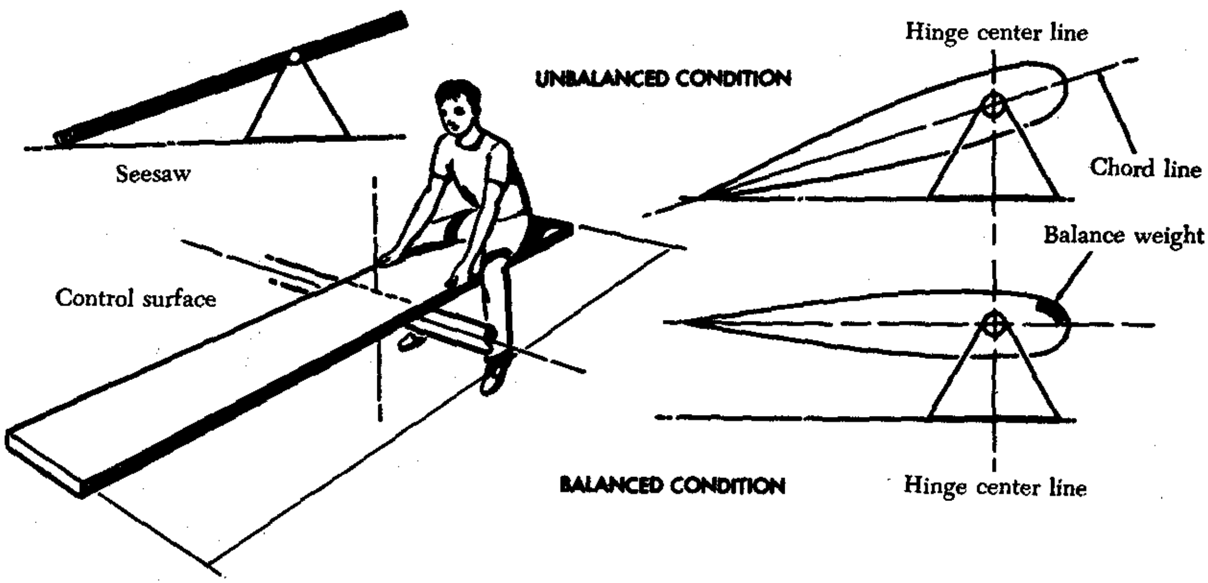


FIGURE 2-76. (A) Unbalanced, (B) Balanced conditions.

seated in different positions thereon. Figure 2-77 illustrates a seesaw with an 80-lb. child seated at a distance of 6 ft. from the fulcrum point of the seesaw. The weight of the child tends to rotate the seesaw in a clockwise direction until it touches the ground. To bring the seesaw into a level or balanced condition, a child is placed on the opposite end of the seesaw. The child must be placed at a point equal to the moment of the child on the left side of the seesaw.

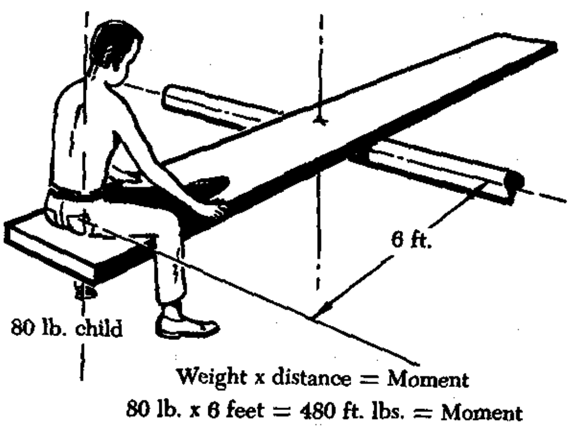


FIGURE 2-77. Moment.

Assume that the child is placed a distance of 8 ft. to the right of the fulcrum point. A simple formula can be used to determine the exact weight that the child must have to balance or bring the seesaw into a leveled condition.

To produce a balanced condition of the seesaw (or control surface), the counterclockwise moment must equal the clockwise moment. Moment is found by multiplying weight times distance. Therefore, the formula to balance the seesaw is:

$$W_2 \times D_2 = W_1 \times D_1.$$

W_2 would be the unknown weight of the second child. D_2 would be the distance (in feet) from the fulcrum that the second child is seated (8). W_1 would be the weight of the first child (80 lbs.). D_1 would be the distance (in feet) from the fulcrum that the first child is seated (6).

Finding the weight of the second child is now a simple matter of substitution and solving the formula as follows:

$$W_2 \times D_2 = W_1 \times D_1$$
$$W_2 \times 8 = 80 \text{ lbs.} \times 6$$
$$W_2 = \frac{480 \text{ lbs.}}{8}$$
$$W_2 = 60 \text{ lbs.}$$

So the weight of the second child would have to be 60 lbs. To prove the formula:

$$60 \text{ lbs.} \times 8 \text{ ft.} = 80 \text{ lbs.} \times 6 \text{ ft.}$$
$$480 \text{ ft. lbs.} = 480 \text{ ft. lbs.}$$

This would result in a balanced condition of the seesaw since the counterclockwise moments around the fulcrum are equal to the clockwise moments around the fulcrum.

The same effect is obtained in a control surface by the addition of weight. Since most of the repairs to control surfaces are aft of the hinge center line, resulting in a trailing-edge-heavy condition, the weight is added forward of the hinge center line. The correct re-balance weight must be calculated and installed in the proper position.

Re-balancing of Movable Surfaces

The material in this section is presented for familiarization purposes only, and should not be used when re-balancing a control surface. Explicit instructions for the balancing of control surfaces are given in the service and overhaul manuals for the specific aircraft and must be followed closely.

Any time repairs on a control surface add weight fore or aft of the hinge center line, the control surface must be re-balanced. Any control surface that is out of balance will be unstable and will not remain in a streamlined position during normal flight. For example, an aileron that is trailing-edge heavy will move down when the wing deflects upward, and up when the wing deflects downward. Such a condition can cause unexpected and violent maneuvers of the aircraft. In extreme cases, fluttering and buffeting may develop to a degree that could cause the complete loss of the aircraft.

Re-balancing a control surface concerns both static and dynamic balance. A control surface that is statically balanced will also be dynamically balanced.

Static Balance

Static balance is the tendency of an object to remain stationary when supported from its own center of gravity. There are two ways in which a control surface may be out of static balance. They are called underbalance and overbalance.

When a control surface is mounted on a balance stand, a downward travel of the trailing edge below the horizontal position indicates underbalance. Some manufacturers indicate this condition with a plus (+) sign. Figure 2–78A illustrates the underbalance condition of a control surface.

An upward movement of the trailing edge, above the horizontal position (figure 2–78B), indicates overbalance. This is designated by a minus (—) sign. These signs show the need for more or less weight in the correct area to achieve a balanced control surface as shown in figure 2–78C.

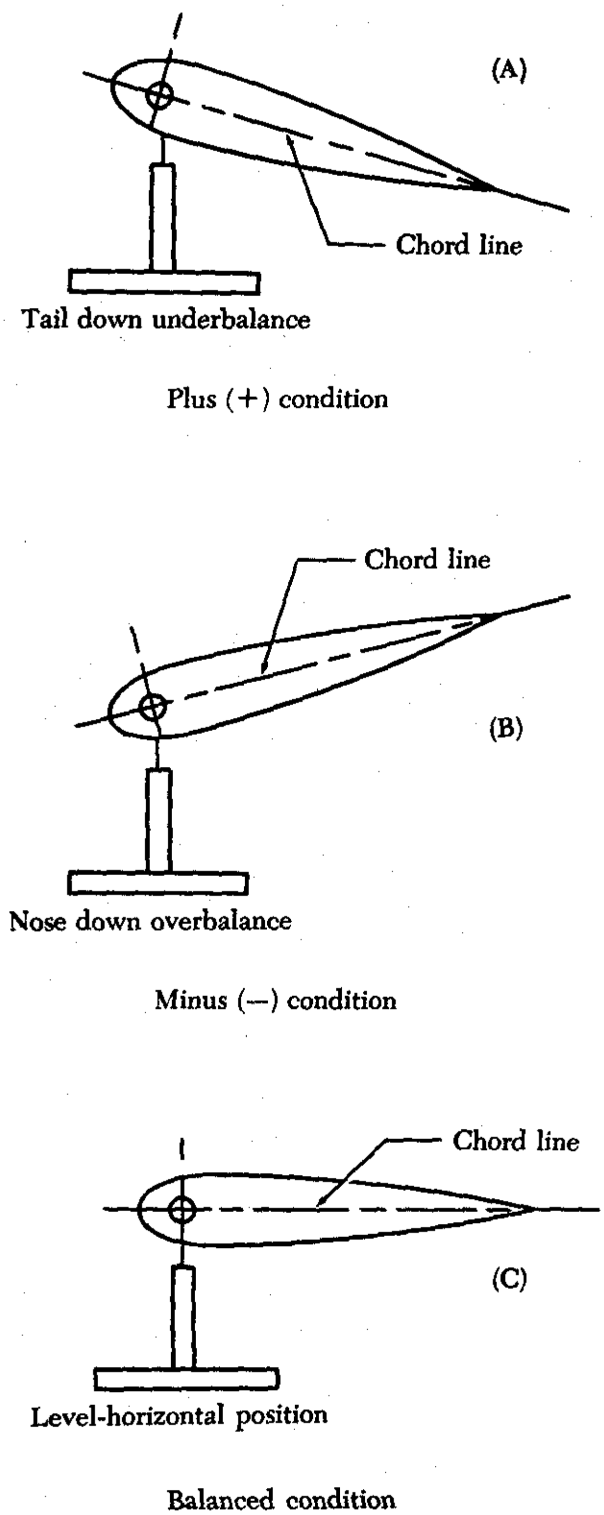


FIGURE 2–78. Control surface static balance.

A tail-heavy condition (static underbalance) causes undesirable flight performance and is not usually allowed. Better flight operations are gained by nose heaviness static overbalance. Most manufacturers advocate the existence of nose-heavy control surfaces.

Dynamic Balance

Dynamic balance is that condition in a rotating body wherein all rotating forces are balanced within themselves so that no vibration is produced while the body is in motion. Dynamic balance as related to control surfaces is an effort to maintain balance when the control surface is submitted to movement on the aircraft in flight. It involves the placing of weights in the correct location along the span of the surfaces. The location of the weights will, in most cases, be forward of the hinge center line.

RE-BALANCING PROCEDURES

Requirements

Repairs to a control surface or its tabs generally increase the weight aft of the hinge center line, requiring static re-balancing of the control surface system as well as the tabs. Control surfaces to be rebalanced should be removed from the aircraft and supported, from their own points, on a suitable stand, jig, or fixture (figure 2-79).

Trim tabs on the surface should be secured in the neutral position when the control surface is mounted on the stand. The stand must be level and be located in an area free of air currents. The control surface must be permitted to rotate freely about the hinge points without binding. Balance condition is determined by the behavior of the trailing edge when the surface is suspended from its hinge points. Any excessive friction would result in a false reaction as to the overbalance or underbalance of the surface.

When installing the control surface in the stand or jig, a neutral position should be established with the chord line of the surface in a horizontal position (figure 2-80). Use a bubble protractor to determine the neutral position before continuing balancing procedures. Sometimes a visual check is all that is needed to determine whether the surface is balanced or unbalanced.

Any trim tabs or other assemblies that are to remain on the surface during balancing procedures should be in place. If any assemblies or parts must be removed before balancing, they should be removed.

METHODS

At the present time, four methods of balancing (re-balancing) control surfaces are in use by the various manufacturers of aircraft. The four methods are commonly called the calculation method,

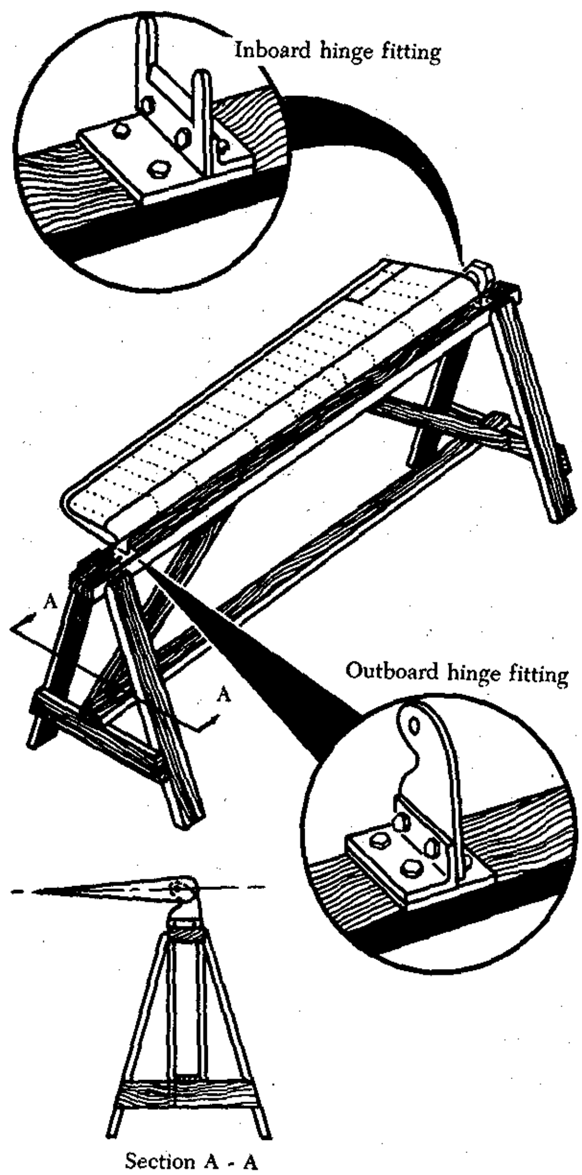


FIGURE 2-79. Field type balancing jigs.

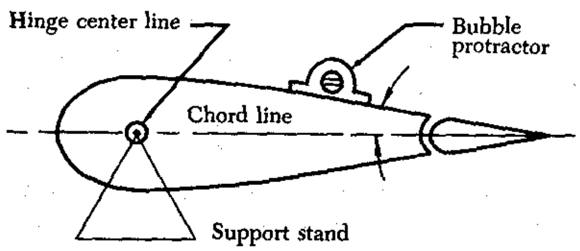


FIGURE 2-80. Establishing a neutral position.

scale method, trial weight (trial and error) method, and component method.

The calculation method of balancing a control surface is directly related to the principles of balancing discussed previously. It has one advantage over the other methods in that it can be performed without removing the surface from the aircraft.

In using the calculation method, the weight of the material from the repair area and the weight of the materials used to accomplish the repair must be known. Subtracting the weight removed from the weight added will give the resulting net gain in the amount added to the surface.

The distance from the hinge center line to the center of the repair area is then measured in inches. This distance must be determined to the nearest one-hundredth of an inch (figure 2–81).

The next step is to multiply the distance times the net weight of the repair. This will result in an in.-lbs. (inch-pounds) answer. If the in.-lbs. result of the calculations is within specified tolerances, the control surface will be considered balanced. If it is not within specified limits, consult the manufacturer's service manuals for the needed weights, material to use for weights, design for manufacture, and installation locations for addition of the weights.

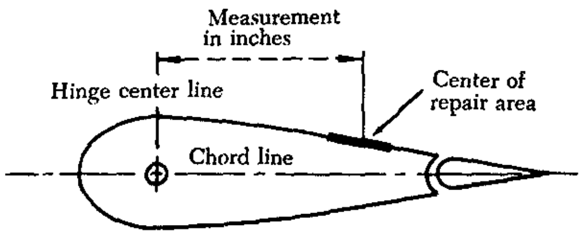


FIGURE 2–81. Calculation method measurements.

The scale method of balancing a control surface requires the use of a scale that is graduated in hundredths of a pound. A support stand and balancing jigs for the surface are also required. Figure 2–82 illustrates a control surface mounted for rebalancing purposes. Use of the scale method requires the removal of the control surface from the aircraft.

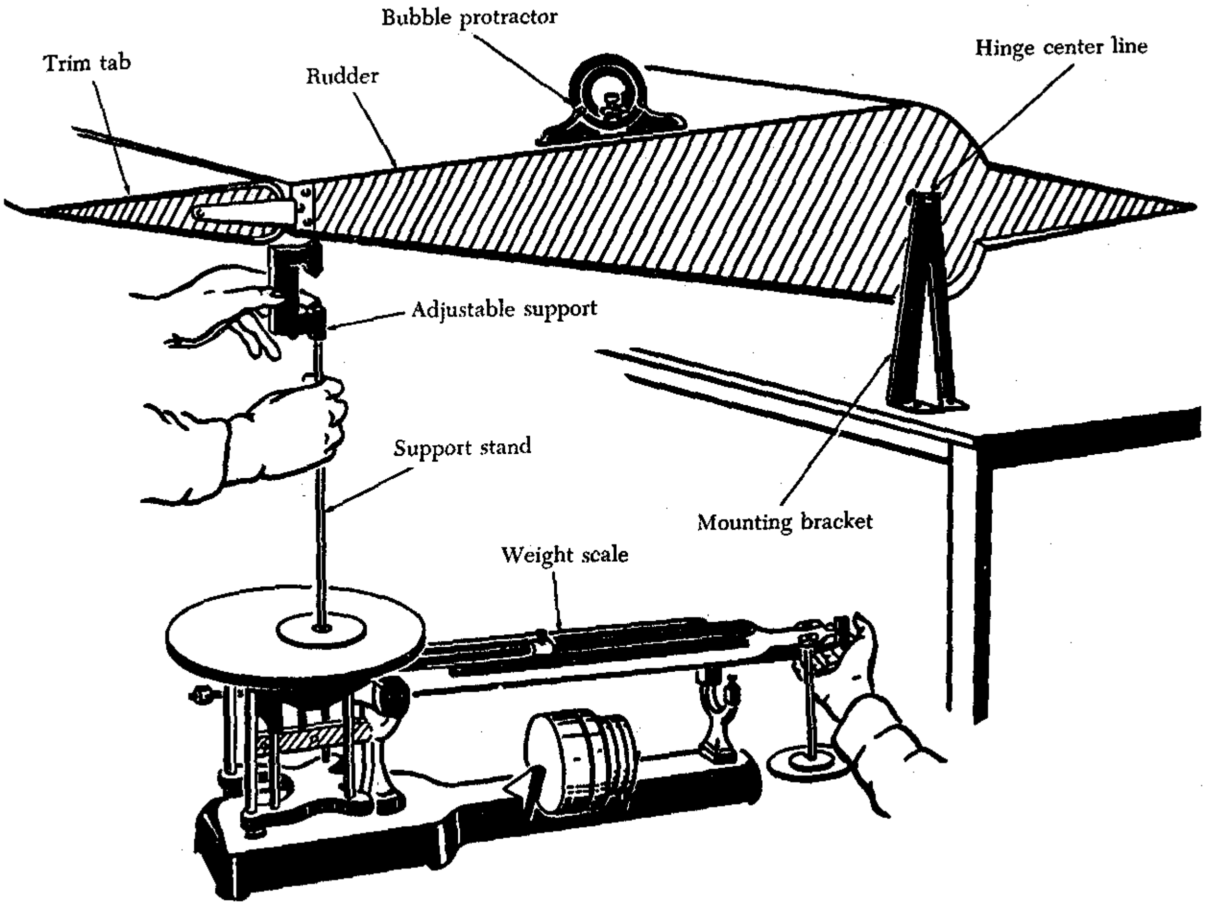


FIGURE 2–82. Balancing setup.